

# ***COOPERATIVE MISSION CONCEPTS USING BIOMORPHIC EXPLORERS***

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## EXECUTIVE SUMMARY

Inspired by the immense variety of naturally curious explorers (insects, animals, and birds), their well integrated biological sensor-processor suites that are efficiently packaged in compact but highly dexterous forms, and their complex, intriguing, cooperative behaviors, this study focuses on "Biomorphic Explorers" and presents cooperative biomorphic planetary exploration scenarios. Biomorphic explorers are defined as small, dedicated, low-cost explorers that capture some of the key features of biological systems. These include versatile mobility, adaptive distributed controls, and cooperative behavior. Biomorphic explorers offer the potential to obtain significant scientific payoff at a low cost by utilizing the power of a large number of cooperatively functioning units. This is analogous to operational principles of navigation and intercommunication used by social insects such as honeybees and ants.

A classification of these explorers based on their mobility and ambient environment divides them broadly into biomorphic flight systems and biomorphic surface/subsurface systems. Another classification is based on size: envelope volume and mass. Three general overlapping categories are defined: 'A' = 1 to 20 cm<sup>3</sup>, < 20 g; 'B' = 10 to 200 cm<sup>3</sup>, < 200 g; and 'C' = 100 to 2000 cm<sup>3</sup>, < 2 kg. Example candidates in each category are presented. Such biomorphic explorers can potentially enable new capabilities in cooperative mission scenarios along with orbiters, landers, rovers, and/or balloons. Biomorphic flight systems, in particular, have the potential for substantially higher mobility (in speed, range, and terrain independence). Biomorphic flight systems can even be made to deliver instrument payload/other biomorphic explorers to target sites, greatly extending the utility of those explorers. Cooperative exploration with an orbiter, a lander/balloon, a rover, and a multitude of inexpensive biomorphic explorers would allow comprehensive exploration at low cost and with broad spatial coverage. For orbiters, landers, rovers, and manned missions, flight systems in particular provide a means for exploring beyond the visual range of onboard cameras. They aid in identifying targets of scientific interest and determining optimal pathways to those targets. The biomorphic flight system itself can be designed to seek out features of interest, crash at the target site, and then act as a homing beacon for further experiments. An important application is to use them as scouts in future planetary exploration where they would look for samples/sites of interest in heretofore inaccessible locations. The mission concepts described in this study focus on the biomorphic flight systems in the size B regime, namely biomorphic gliders, seedwing flyers and powered flyers. Considerations of low mass, long range, and high payload mass fraction led to the choice of the glider as the subject for a conceptual system design. For example, the Biomorphic Glider provides a combination of low mass (< 100 g), high payload fraction (> 50%), and large terrain coverage (50-100 km in 10 minutes).

The mission concepts developed in this study are targeted toward the following key objectives: (1) Atmospheric Information Gathering: Distributed Multiple Site Measurements, (2) Close-Up Imaging and Exobiology Site Selection, (3) Deployment of Payload: Instruments/Crawlers, etc., and (4) Sample Return Reconnaissance. This study shows that biomorphic glider missions can be implemented in several different scenarios because of their low mass and hence can be sent rapidly in the mass reserves of upcoming orbiter, lander, or balloon missions. The study concludes that biomorphic explorers is a technology push on

- (1) miniaturization & integration of payload,
- (2) cooperative communication innovations such as monolithic transceiver integration and dynamic networks of self-routing optimal comm interlinks,
- (3) biomorphic flight systems, and
- (4) biomechatronic surface system innovations.

## BIOMORPHIC EXPLORERS

- **SMALL, DEDICATED, LOW-COST EXPLORERS THAT CAPTURE SOME OF THE KEY FEATURES OF BIOLOGICAL EXPLORERS**
  - **VERSATILE MOBILITY: aerial, surface, subsurface, and in fluids**
  - **ADAPTIVE, DISTRIBUTED OPERATION**
  - **BIOMORPHIC COOPERATIVE BEHAVIOR**
- **CONDUCTED WORKSHOP, AUG 19-20, 1998**
  - **SPONSORED BY TAP, SESPD, CISM, NMP**
  - **VERY SUCCESSFUL; OVER 150 PARTICIPANTS**

# Biomorphic Explorers: Classification (Based on Mobility and Ambient Environment)

## Biomorphic Explorers

Aerial

Surface/Subsurface

### Biomorphic Flight Systems

### Biomorphic Surface Systems

### Biomorphic Subsurface Systems



Seed Wing



Honey Bee



Soaring Bird



Humming Bird



Ant



Snake



Centipede



Earthworm



Jelly Fish



Germinating Seed

Examples of biological systems that serve as inspiration for designing the biomorphic explorers in each class

## BIOMORPHIC EXPLORERS

### Biomorphic Explorers: Classification (Based on Mobility and Ambient Environment)

#### Biomorphic Explorers

##### Aerial

##### Biomorphic Flight Systems



Seed Wing Flyer (60 g)

Ornithopter



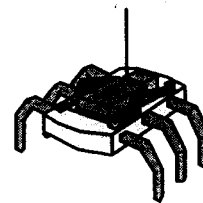
Glider (75 g)



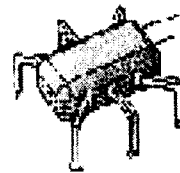
Powered Flyer

##### Surface/Subsurface

##### Biomorphic Surface Systems



Hexapod  
(1-2 kg)



Reconfigurable  
Legs/Feet



Artificial Earthworm

##### Biomorphic Subsurface Systems



Artificial Jelly Fish

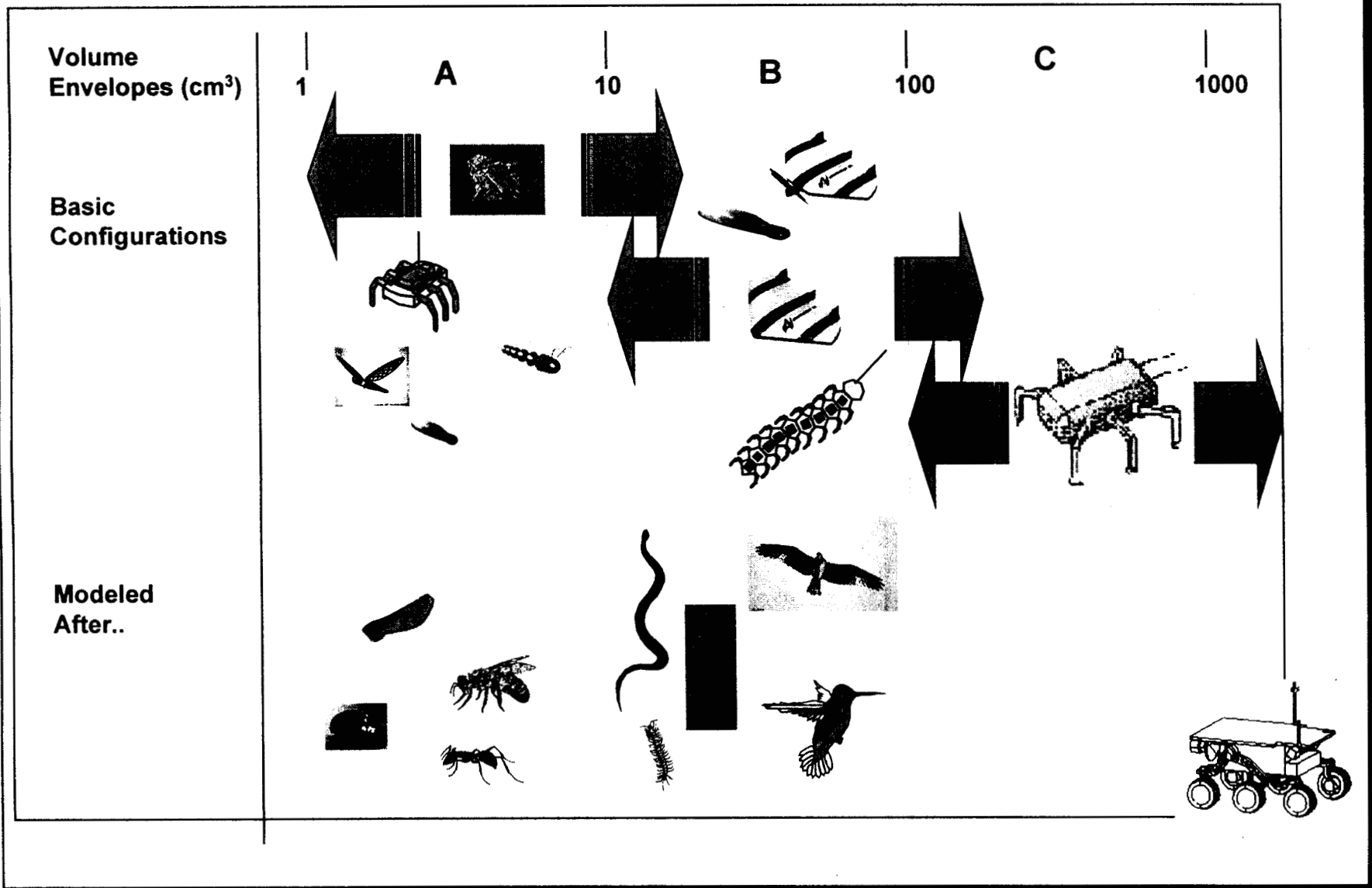


Worm Robot (85 g)

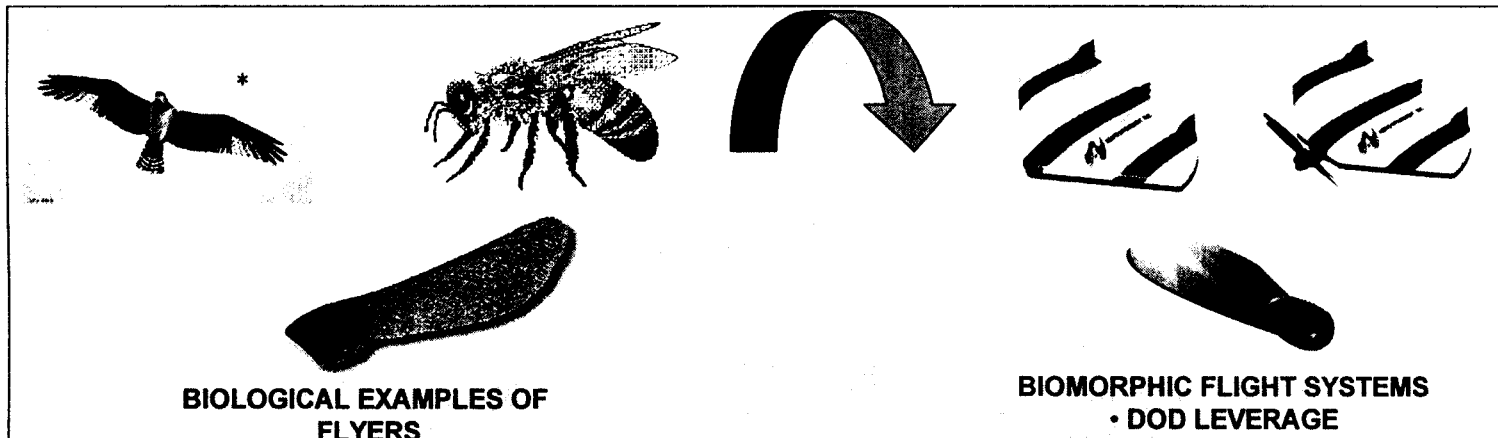
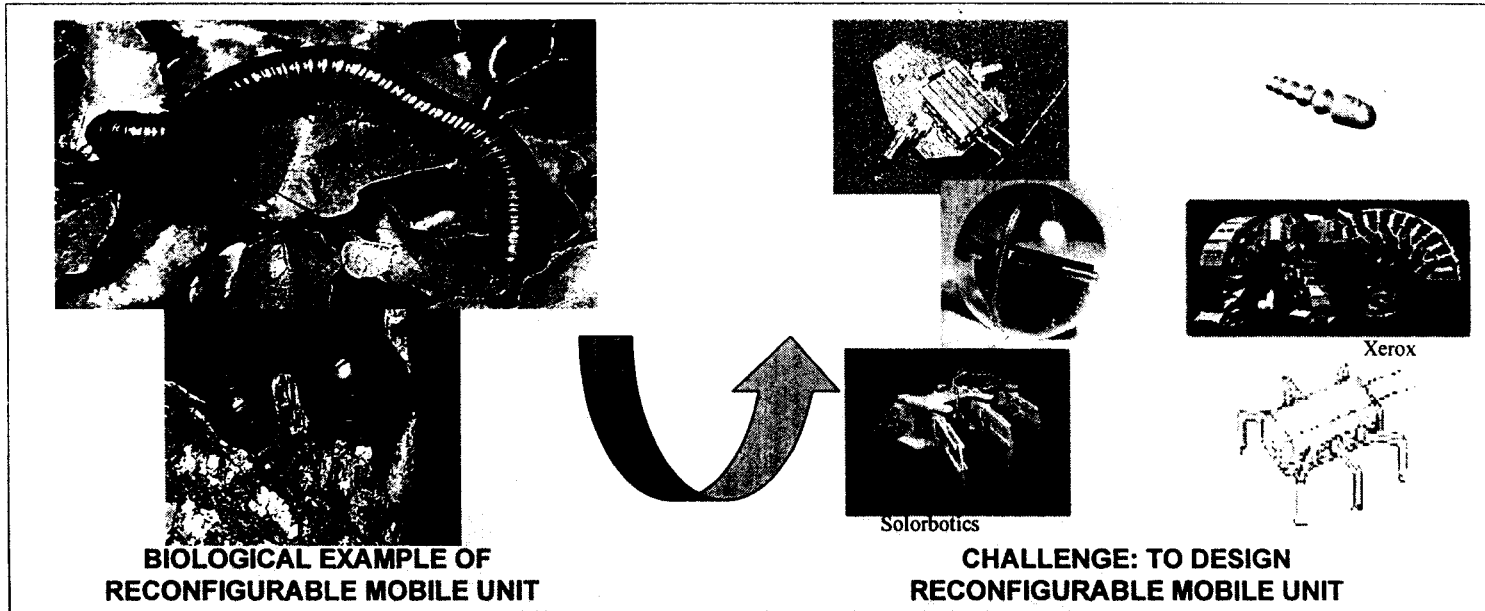
Candidate biomorphic explorers on the drawing board, with mass of design under study in 1998 in parentheses

\*<http://www.gregscott.com/rwscott/rwscott.htm>

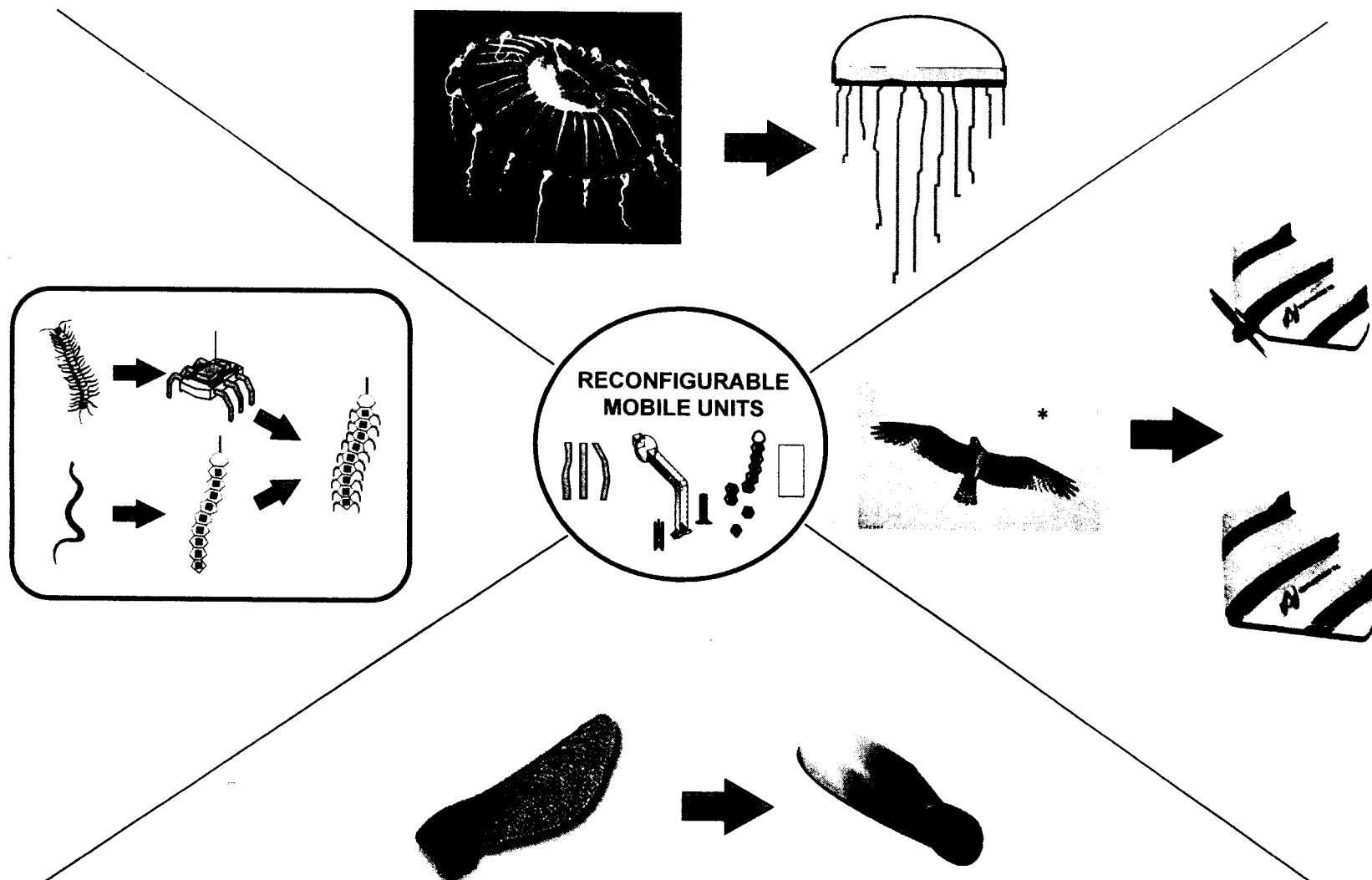
# BIOMORPHIC EXPLORERS: SIZE BASED CLASSIFICATION



# BIOMORPHIC EXPLORERS: VERSATILE MOBILITY



# ADVANCED MOBILITY FOR BIOMORPHIC EXPLORERS





## COORDINATED/COOPERATIVE EXPLORATION SCENARIO

BIOMORPHIC FLYERS

- ATMOSPHERIC INFO GATHERING:
- DISTRIBUTED MULTIPLE SITE MEASUREMENTS
- CLOSE-UP IMAGING, EXOBIOLGY SITE SELECTION
- DEPLOY PAYLOAD: INSTRUMENTS/CRAWLERS

LANDER/  
ROVER

INFO DOWNLINK  
TO LANDER

JAVELIN  
COM PORT 2

BIOMORPHIC CRAWLERS  
EXOBIOLGY

INACCESSIBLE  
AREA

SURFACE

PENETRATOR

INFO DOWNLINK  
TO PENETRATOR

COOPERATIVE ORGANIZATION OF LANDER, ROVER, AND A VARIETY OF INEXPENSIVE BIOMORPHIC EXPLORERS WOULD ALLOW COMPREHENSIVE EXPLORATION AT LOWER COST WITH BROADER COVERAGE.

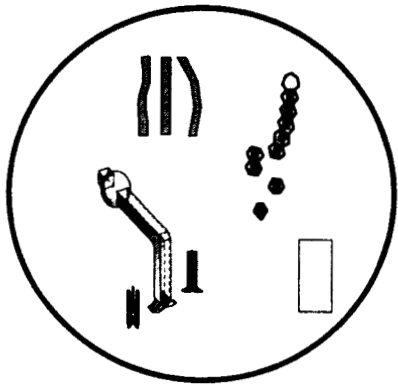
## BIOMORPHIC EXPLORERS

- **PAYOFF**
- **BIOMORPHIC EXPLORERS, IN COOPERATION WITH CURRENT EXPLORATION PLATFORMS SUCH AS LANDERS AND ORBITERS, CAN ENABLE**
  - **EXPLORATION OF CURRENTLY INACCESSIBLE AND/OR HAZARDOUS LOCATIONS**
  - **MUCH BROADER COVERAGE OF EXPLORATION SITES**
  - **EXPLORATION AT LOWER COST**

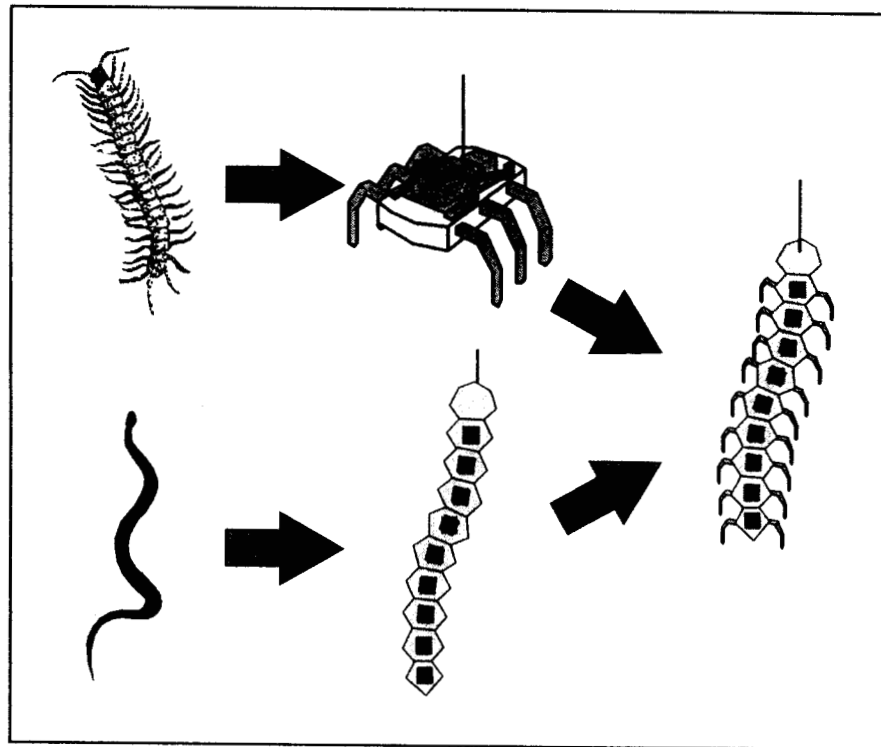
# BIOMORPHIC SURFACE/SUBSURFACE SYSTEMS

- BIOMORPHIC SURFACE/SUBSURFACE SYSTEMS ARE A UNIQUE COMBINATION OF RECONFIGURABLE MOBILE UNITS AND THEIR CONTROL BY ADAPTIVE, FAULT-TOLERANT ALGORITHMS TO AUTONOMOUSLY MATCH WITH THE CHANGING AMBIENT/TERRAIN CONDITIONS. THEY PERFORM IN COOPERATIVE MODES TO ENABLE SCIENCE RETURN THAT IS CURRENTLY UNAVAILABLE

## RECONFIGURABLE MOBILE UNITS

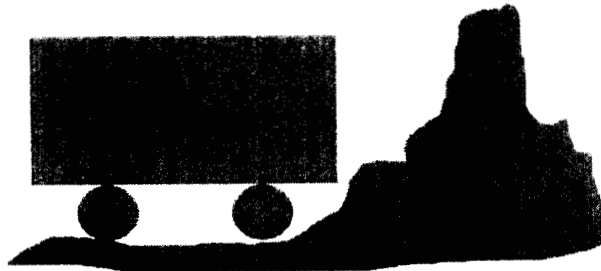


## BIOMORPHIC CONTROL

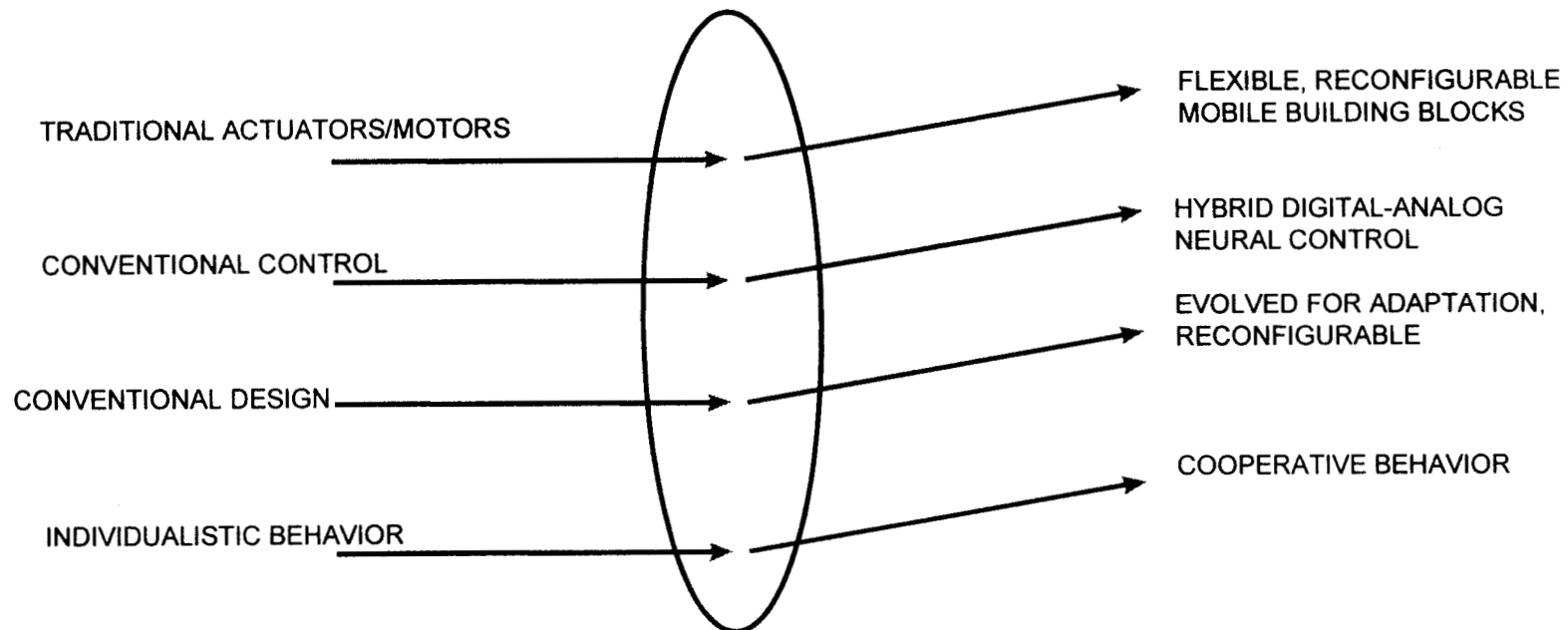


## MOTIVATION: PARADIGM SHIFT FOR ENHANCED SCIENCE RETURN

### CURRENT ROVERS



### BIOMORPHIC MICROEXPLORERS

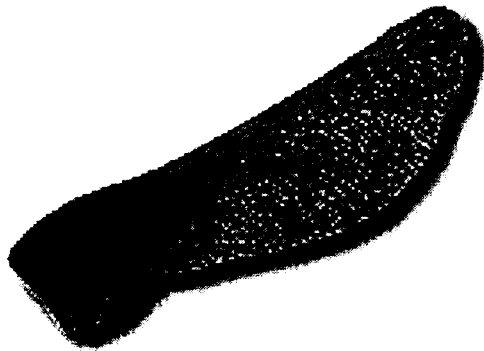


# Biomorphic Flight Systems: Vision

- Extended reach over all kinds of terrain
- Unique perspective for imaging
- Many flyers work in cooperation with orbiters, landers, larger aircraft, and balloons to enable new missions to reach currently inaccessible locations

# BIOMORPHIC FLIGHT SYSTEMS

## JPL-AEROVIRONMENT COLLABORATION



a. Seed Wing Pod

TOTAL MASS: 57 g →  
PAYLOAD MASS: 48 g



b. Seed Wing Pod Flyer



c. Biomorphic Glider

← TOTAL MASS: 57 g  
PAYLOAD MASS: 32 g

TOTAL MASS: 57 g →  
PAYLOAD MASS: 6 g



d. Biomorphic Flyer

Biomorphic flight systems offer rapid mobility and extended reach. For comparison the above illustrates for the same total mass of the system, the respective payload fractions in each case (more detail page 91)

# Biomorphic Gliders

- Small, simple, low-cost system ideal for reconnaissance and wide-area dispersion of sensors and small experiments.
- Payload mass fraction higher (50-70%) compared to powered flyers.



## Design Goals:

- Small total mass, ~100 grams
- High payload mass fraction, >50%
- Mobility: L/D ~5, controlled flight, autonomous navigation using Sun position
- Captures features of soaring birds, utilizing rising currents in the environment

# Biomorphic Glider Mission Concept

- **Mission Objective**

- Up-close, high-resolution imagery of targeted sites.
- In-situ surface chemical/mineralogical measurement to augment imagery.
- Atmospheric survey.
- Reconnaissance for lander/rover mission planning (site selection).

- **Deployment**

- Airborne platforms (balloons, larger aircraft)
- Space (entry probe)

- **Payloads**

- MEMS chem, soil oxidation, or pH
- Temperature and pressure
- Imaging camera
- IR sensor

- **Flight Profile**

- The deployment platform carries several gliders. Gliders are released after identifying a target site and specifying a flight heading, or they fly a pre-programmed flight trajectory (based on Sun angle).
- The gliders fly to the surface, collecting atmospheric data (temperature and pressure) and taking pictures.
- After landing, each glider conducts a surface experiment, which is analyzed using a MEMS sensor for presence of key trace elements or soil properties.
- The glider then transmits the data to the deployment platform or other relay.





## $\mu$ Flyers - Powered Vehicle

- Payload mass fraction 10 to 20%.
- Scaling: Span  $\sim$  Mass<sup>1/2</sup>
- Trade-off between payload mass and range.
- Launch from landers, rovers, entry probes, or larger aircraft.
- Reconnaissance and small sensor/experiment dispersion



### Representative design parameters:

- Total Mass = 57 g
- Payload Mass = 6 g
- Wingspan = 0.194 m
- Wing Area = 0.019 m<sup>2</sup>
- Volume = 380 cm<sup>3</sup>
- Flight Speed = 84 m/s
- Range = 10 km
- Duration = 120 s
- Glide Ratio = 5.3
- Starting Alt. = 0 km

• Performance calculations based on conditions at 5 km altitude on Mars.

# Powered Mission Concept

- **Mission Objective**

- Imagery of over-the-horizon terrain and in-situ surface chemical/mineralogical measurement for rover mission planning (site selection).

- **Deployment**

- Lander

- **Payloads**

- MEMS sensors for chemistry, soil oxidation, or pH
- Imaging camera
- Temperature and Pressure
- IR sensor

- **Flight Profile**

- The rover is equipped with several  $\mu$ Flyers. A mechanical spring is used to launch the  $\mu$ Flyer after specifying a flight heading (Sun angle).
- The  $\mu$ Flyer relays imagery to the lander.
- After landing, each glider conducts a surface experiment, which is analyzed using a MEMS sensor for presence of key trace elements.
- The  $\mu$ Flyer, equipped with a small solar cell, then acts as a radio beacon for rover navigation.
- The rover can also be equipped with  $\mu$ Flyers to help find suitable pathways.

# Seed Wing Flyers

- Simpler and smaller than parachute on small scale for dispersion of sensors and small experiments.
- Slow Descent Rate  $\sim 5$  m/s (at surface of Mars)

## Design Goals:

- Small total mass,  $\sim 100$  g
- High payload mass fraction,  $> 80\%$
- Captures key features of slow and stable descent as observed in Samaras, such as maple seeds



Maple Seed Samara

# Seed Wing Mission Concept

- **Mission Objective**

- Wide-area dispersion of in-situ surface chemical/mineralogical measurement to augment imagery.
- Atmospheric survey.
- Reconnaissance for lander/rover mission planning (site selection).

- **Deployment**

- Entry probe or airborne platform (glider, balloon, powered a/c)

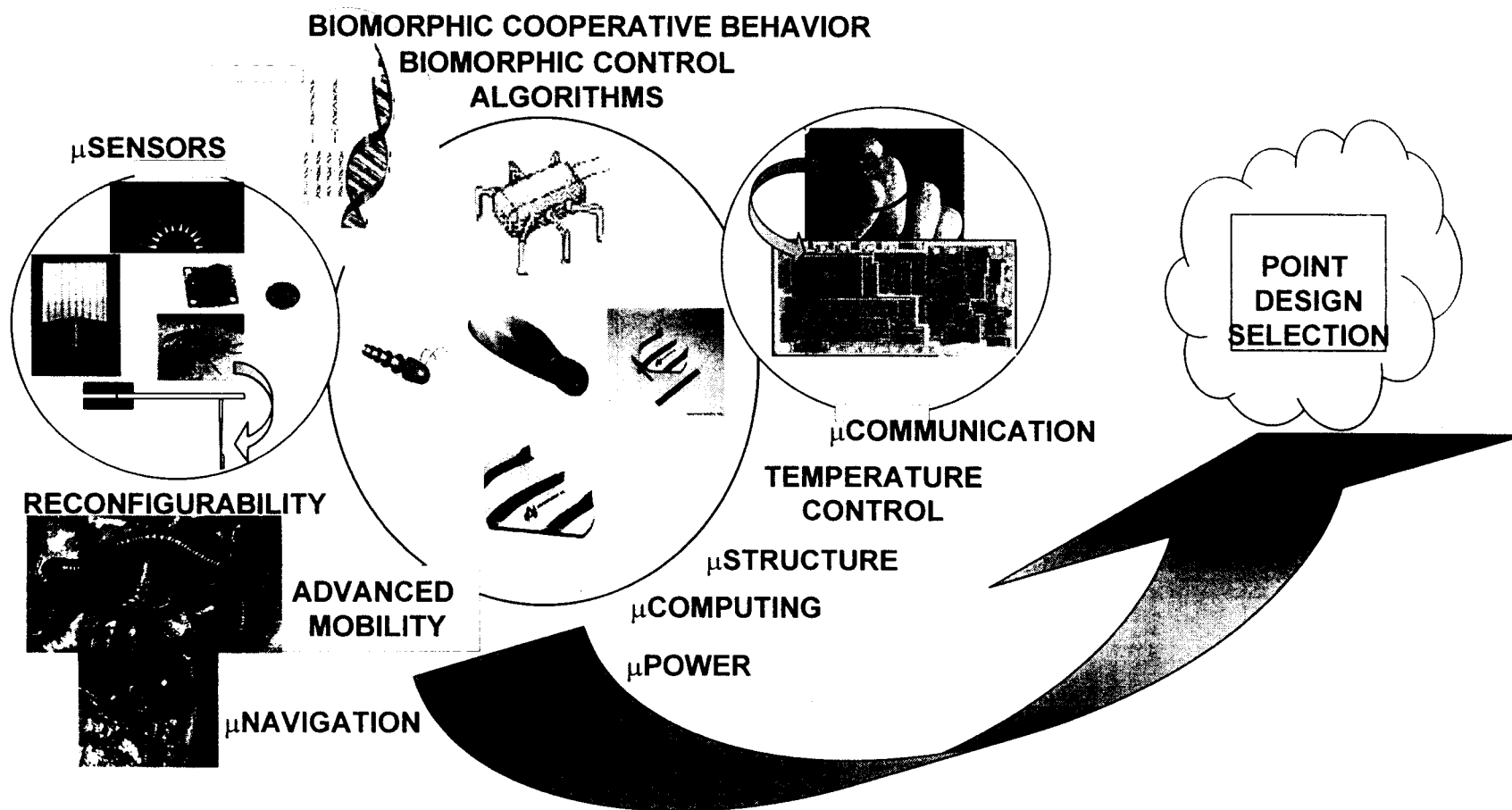
- **Payloads**

- MEMS sensors for chemistry, soil oxidation, or pH
- Temperature and Pressure

- **Flight Profile**

- Seed wings are sequentially deployed from another airborne platform (glider, balloon) or entry probe.
- Each seed wing autorotates to the surface, collecting atmospheric data (temperature and pressure).
- After landing, each seed wing conducts a surface experiment using pyrotechnic or chemical test, which is analyzed using a MEMS sensor for presence of key trace elements. Also, the seed wing could deploy a biomorphic surface/subsurface explorer such as the worm robot
- The orbiter or airborne platform emits a signal initiating sequential download of data from each seed wing. A phased array antenna is used to locate the source and recover the data.

# Biomorphic Explorer: Conceptual Design



## SOME OF THE ISSUES BEING ADDRESSED:

- \* SYSTEM DESIGN/INTEGRATION
- \* COMMUNICATION NEEDS
- \* VERSATILE MOBILITY DESIGNS
- \* CHOICE OF PAYLOAD (SENSORS)
- \* CONFIGURATION, POWER, SIZE, MASS, SPEED, DEGREES OF FREEDOM
- \* BIOMORPHIC CONTROLS INNOVATION
- \* MISSION REQUIREMENTS AND POTENTIAL

BIOMORPHIC EXPLORERS

COMPARISON OF 1998 BIOMORPHIC SYSTEM DESIGNS

SYSTEM TYPE	MASS (g)	VOLUME (cm <sup>3</sup> )	POWER (W)	SPEED m/s	NUMBER PER MISSION (PAYLOAD ~3 kg)	TERRAIN COVERAGE
BIOMORPHIC FLIGHT SYSTEM						
GLIDER	75	300	3	90	32	ALL TYPES ~50 km -100 km range covered in ~ 10 min
SEED WING FLYER	60	77	2.5	6	25-50 (deployment platform dependent)	ALL TYPES
BIOMORPHIC SURFACE/SUBSURFACE SYSTEM						
WORM ROBOT	85	300	TBD	0.003	30	VERY LIMITED
HEXAPOD	1000-2000	750	5-10	0.1	1	LIMITED ~ 0.06 km range covered in ~ 10 min

\* Needs Innovations of biomechatronic design

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## COMPARISON OF 1998 BIOMORPHIC SYSTEM DESIGNS

Worm robot is an advanced concept in its infancy that awaits development of an innovative biomechatronic design.

Multipods have been extensively worked on, and small quadrupod or hexapod designs using flexible carbon steel legs have been made, which can be smaller than the hexapod designed in 1998. Making a hexapod suitable for the rocky Mars terrain dictated the design of this science-purpose hexapod. Because of its large mass (1-2 kg), for a biomorphic mission, this design would not be amenable to easy multiplicity.

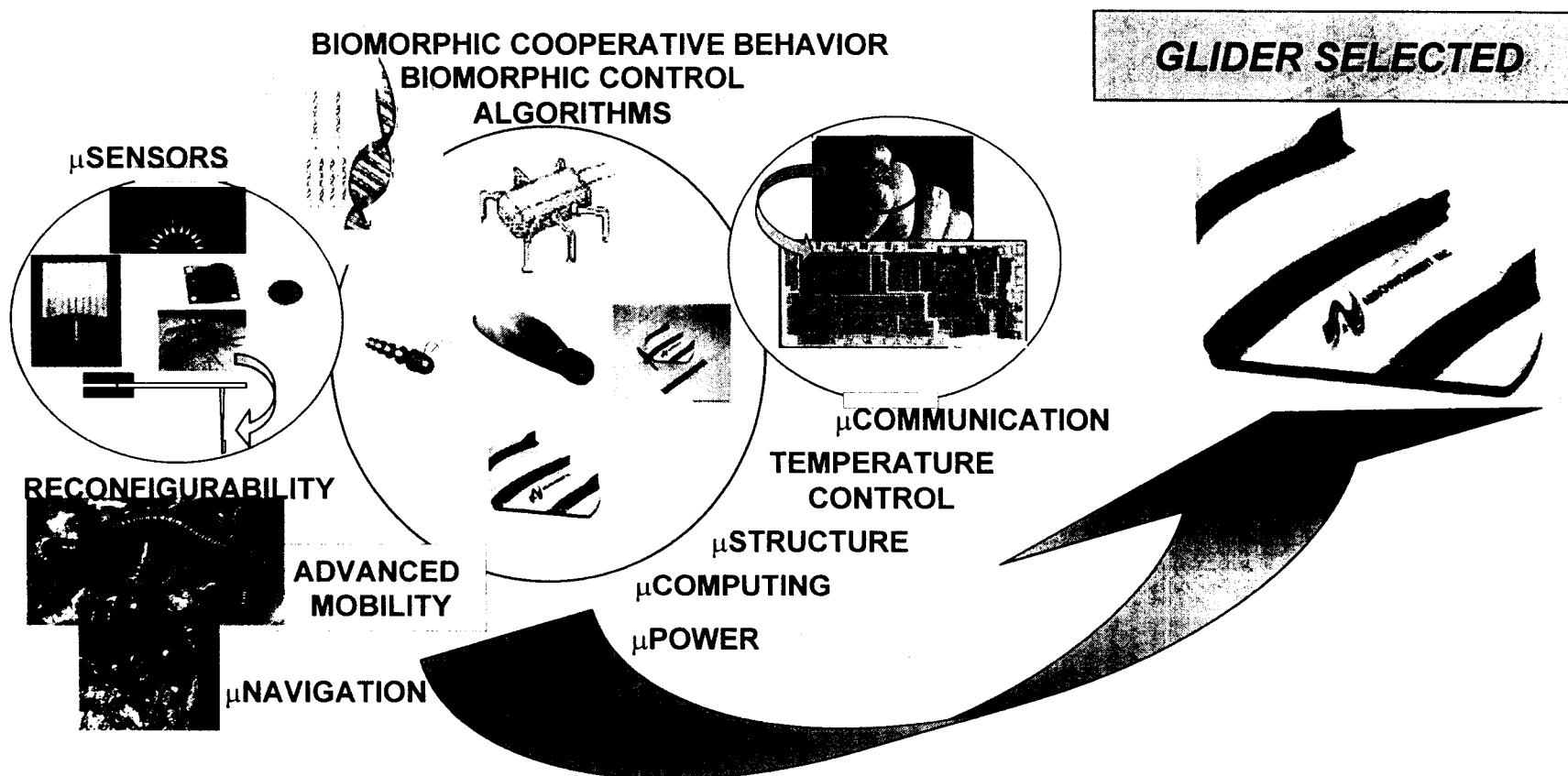
When considering the specific applications of wide-area coverage for site selection via imaging and collecting atmospheric data from multiple points, the glider clearly stands out as the choice because of its low mass, high payload fraction, and long range (terrain coverage of 50-100 km in just about ten minutes). Additionally, the technology to build a small glider can be readily leveraged from the recent developments in micro air vehicles. Therefore, the glider was selected for end-to-end baseline conceptual design development.

## COMPARISON OF DIFFERENT MARS EXPLORER TYPES

PLATFORM	IMAGERY, TARGET, AND SITE CHARACTERISTICS
GLIDERS	<ul style="list-style-type: none"> <li>• IMAGING CLOSE TO CANYON WALLS FOR EXCELLENT SPATIAL RESOLUTION</li> <li>• IN-FLIGHT ATMOSPHERIC MEASUREMENTS, MULTIPLE LOCATIONS, SIMULTANEOUSLY</li> <li>• CAN TRAVERSE RUGGED TERRAIN, LONG RANGE, HIGH COVERAGE DENSITY</li> <li>• EXCELLENT NAVIGATION AND TARGETING CONTROL, PROVIDES SITE DIVERSITY</li> <li>• LOW-COST PLATFORM ALLOWS REDUNDANCY, LOW MISSION RISK, HIGH PAYLOAD FRACTION</li> </ul>
ORBITER	<ul style="list-style-type: none"> <li>• HIGH SPATIAL RESOLUTION POSSIBLE</li> <li>• COMPOSITION POSSIBLE, BUT AT POOR SPATIAL RESOLUTION</li> <li>• STEEP VERTICAL WALLS ARE POORLY RESOLVED</li> </ul>
LANDER	<ul style="list-style-type: none"> <li>• DISTANCE FROM WALLS LEADS TO POOR RESOLUTION</li> <li>• NEAR-FIELD OBSTRUCTIONS MAY LIMIT VIEW OF PRIMARY TARGETS</li> <li>• NO TRAVERSE CAPABILITY</li> </ul>
ROVER	<ul style="list-style-type: none"> <li>• TRAVERSE LIMITED TO 1 TO 3 km OVER PERIOD OF DAYS</li> <li>• CANNOT ACCESS MULTIPLE SITES</li> <li>• CANNOT ACCESS STEEP AND ROUGH WALL SLOPES</li> </ul>
BALLOON	<ul style="list-style-type: none"> <li>• NO ABILITY TO CONTROL TARGET LOCATION</li> <li>• SENSITIVITY TO LOCAL WINDS, RAPID TEMPERATURE AND PRESSURE FLUCTUATIONS</li> </ul>
POWERED AIRCRAFT	<ul style="list-style-type: none"> <li>• LOWER PAYLOAD FRACTION</li> <li>• MORE MASS, MORE POWER, LARGER WINGSPAN, ASSOCIATED ADDITIONAL COSTS</li> <li>• HIGHER COSTS &amp; LARGER SIZE REDUCE MULTIPLICITY</li> </ul>



# Biomorphic Explorer: Conceptual Design



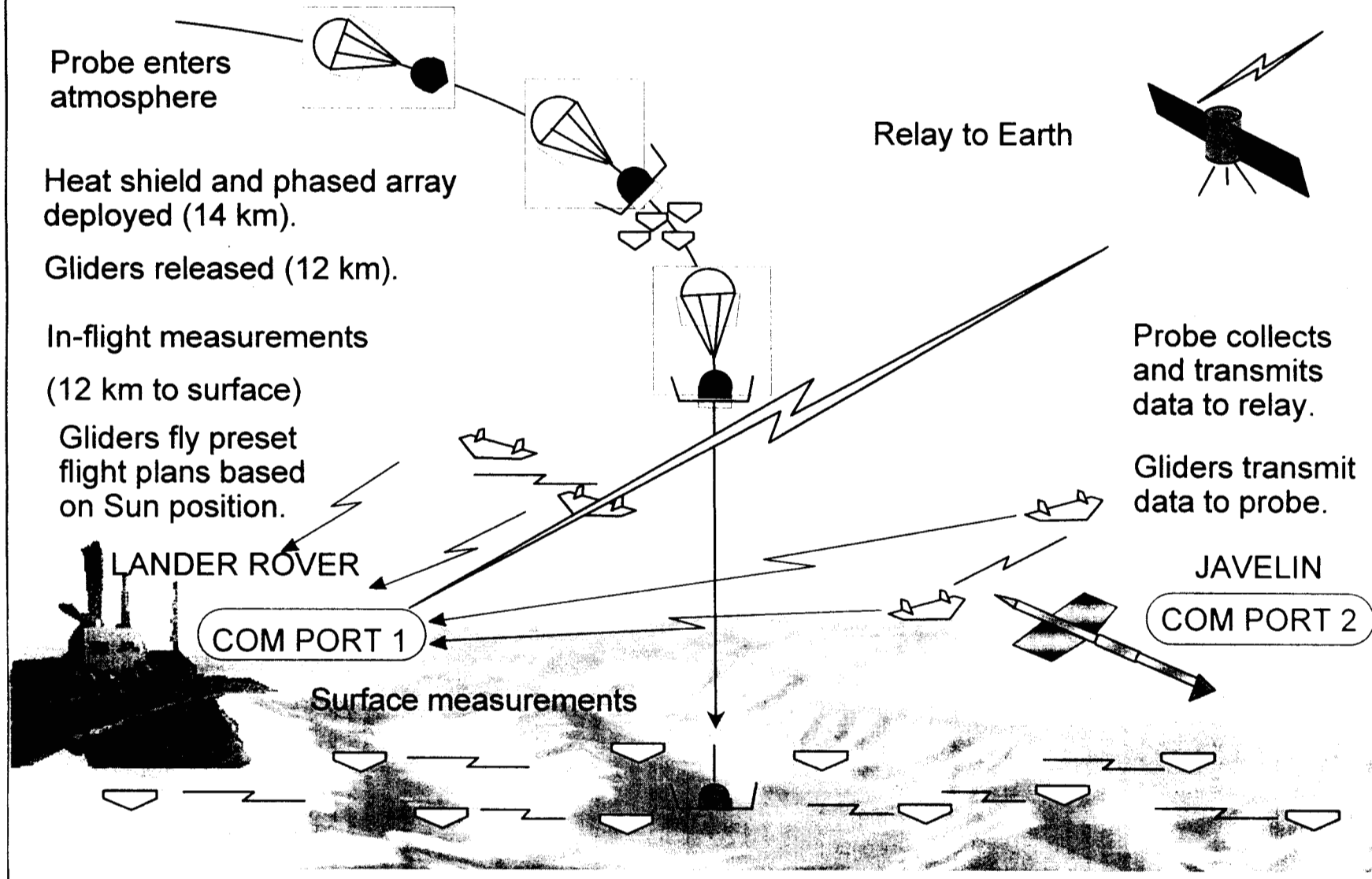
## SELECTION CRITERIA

- LOW MASS/VOLUME
- HIGH PAYLOAD FRACTION
- LARGE RANGE OF MOBILITY
- ACTIVE CONTROL
- IMPLEMENTATION READINESS

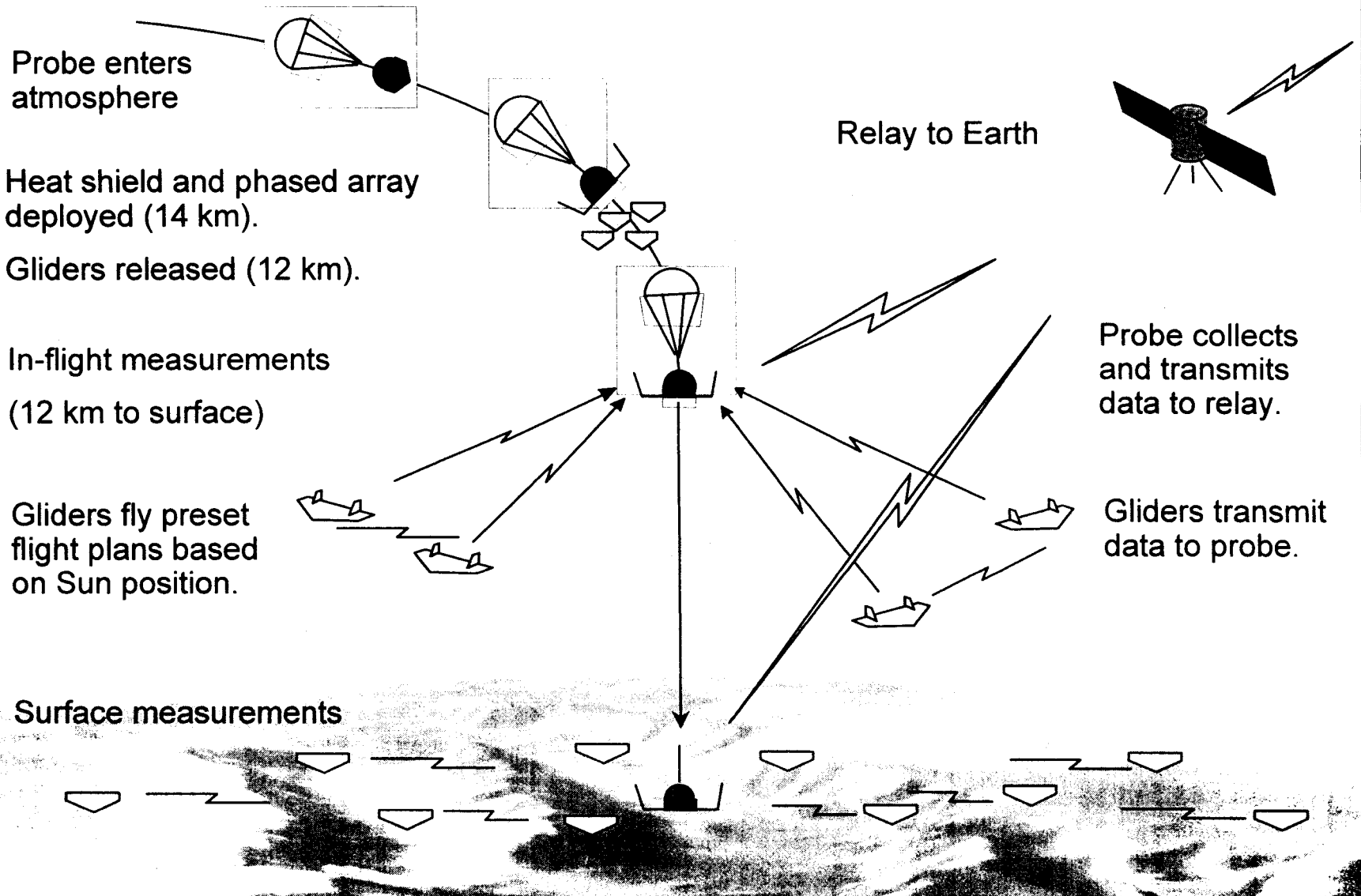
## GLIDER BASELINE DESIGN CHARACTERISTICS

- MASS: 75 g
- PAYLOAD FRACTION : 60 %
- GLIDE RATIO , L/D ~ 5.8
- LARGE RANGE OF AERIAL MOBILITY:  
~ 50 km to 100 km
- LEVERAGE FROM MAV TECHNOLOGY
- VOLUME: 300 cm<sup>3</sup>
- ACTIVE FLIGHT CONTROL
- SOLAR NAVIGATION
- SOARING FLIGHT IN RISING CURRENTS
- COOPERATIVE MISSION: 32 GLIDERS
- COVERAGE AREA: ~ 100 km x 100 km

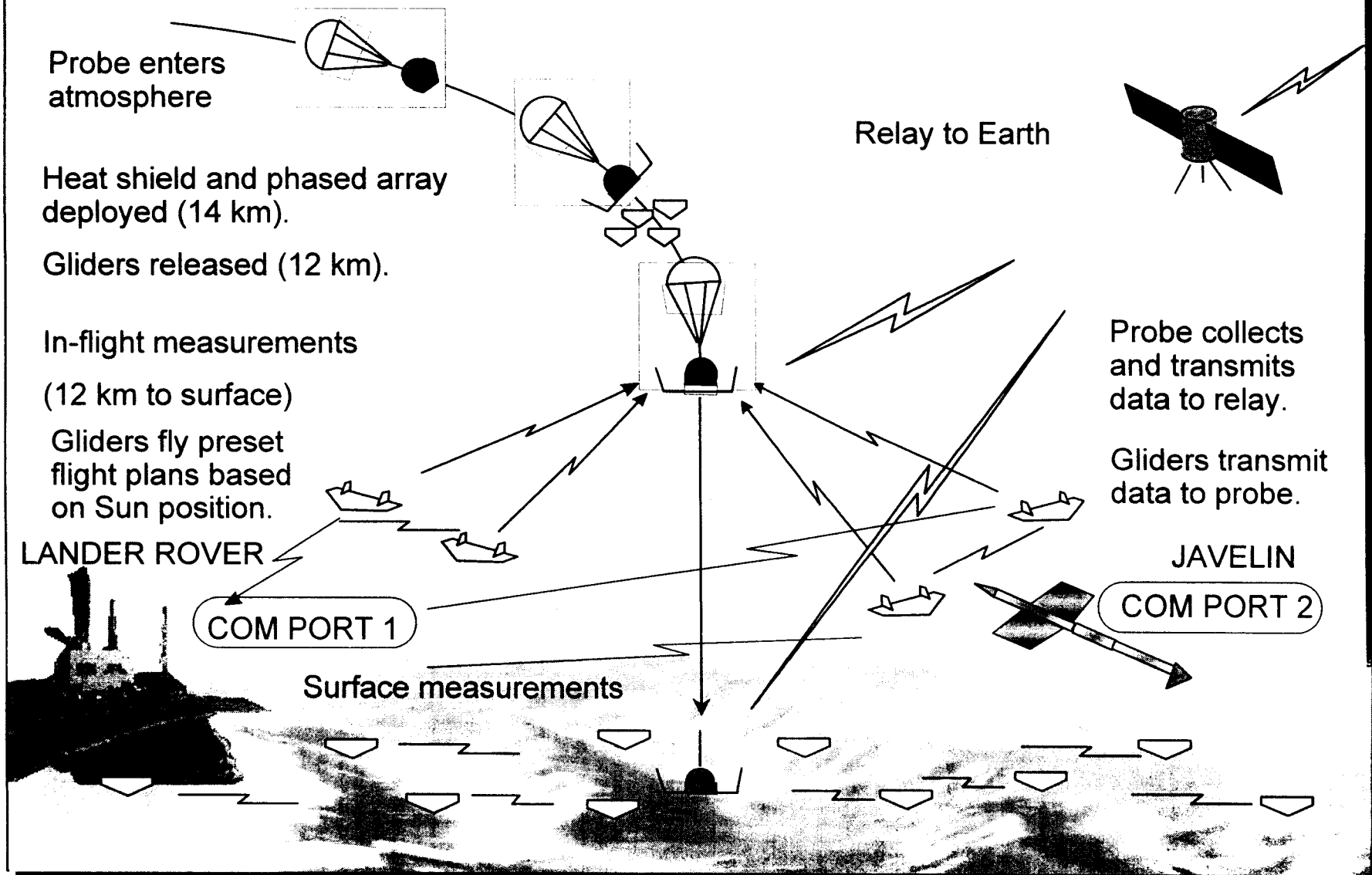
# Biomorphic Glider Deployment Concept: Probe Deploy/Lander Relay



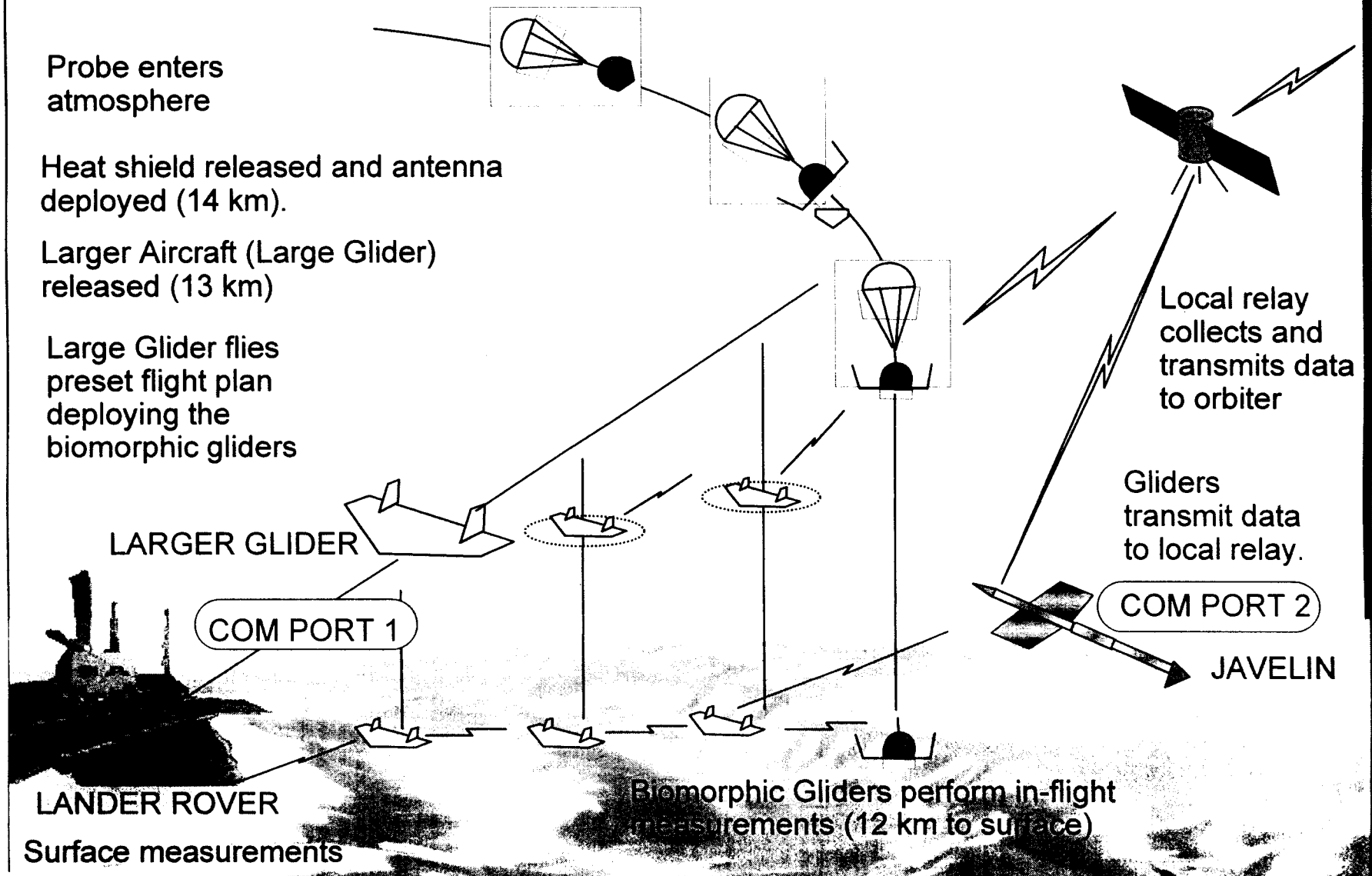
# Biomorphic Glider Deployment Concept: Probe Deploy/Probe Relay



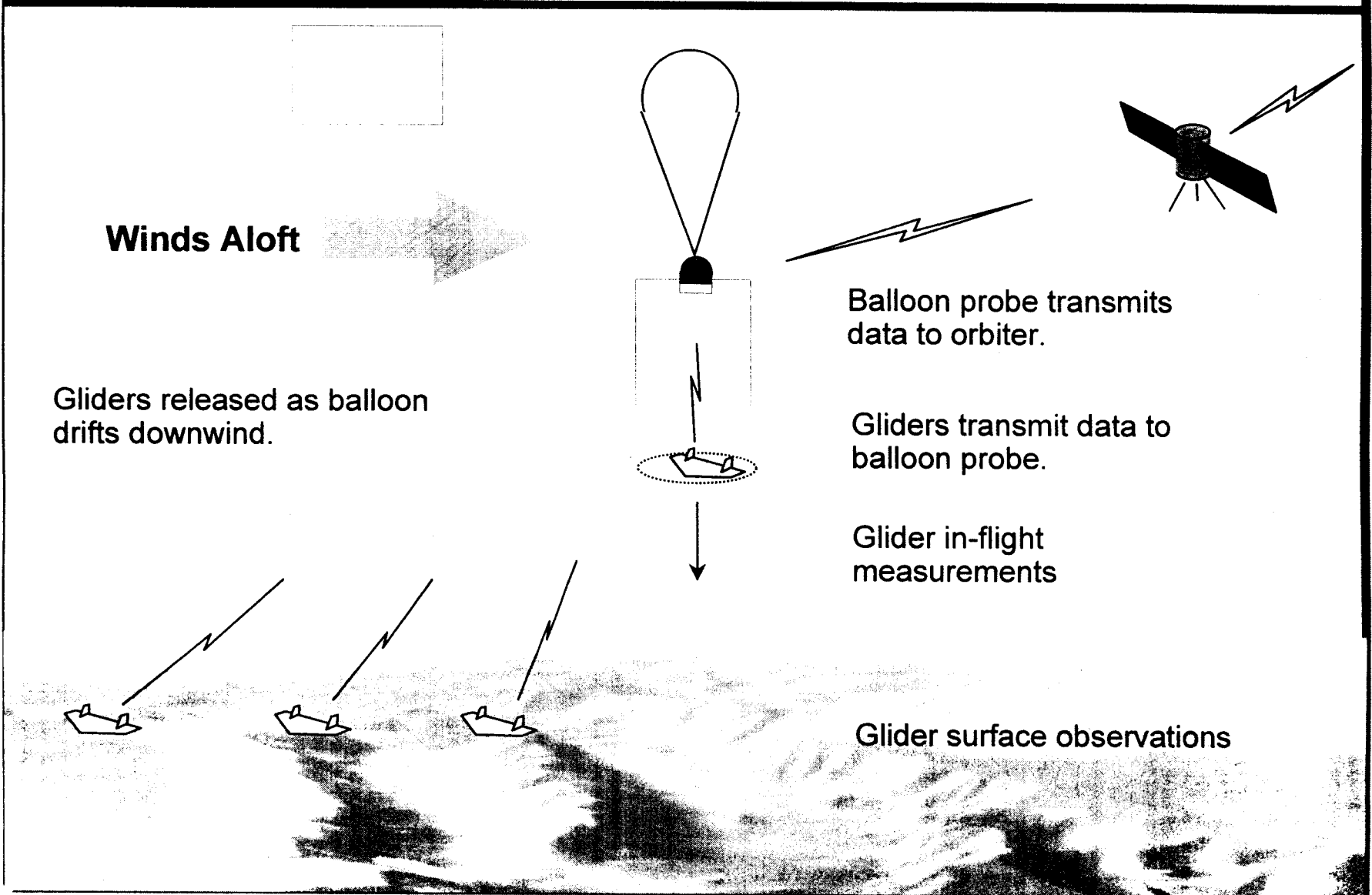
# Biomorphic Glider Deployment Concept: Probe Deploy/Dual Relay



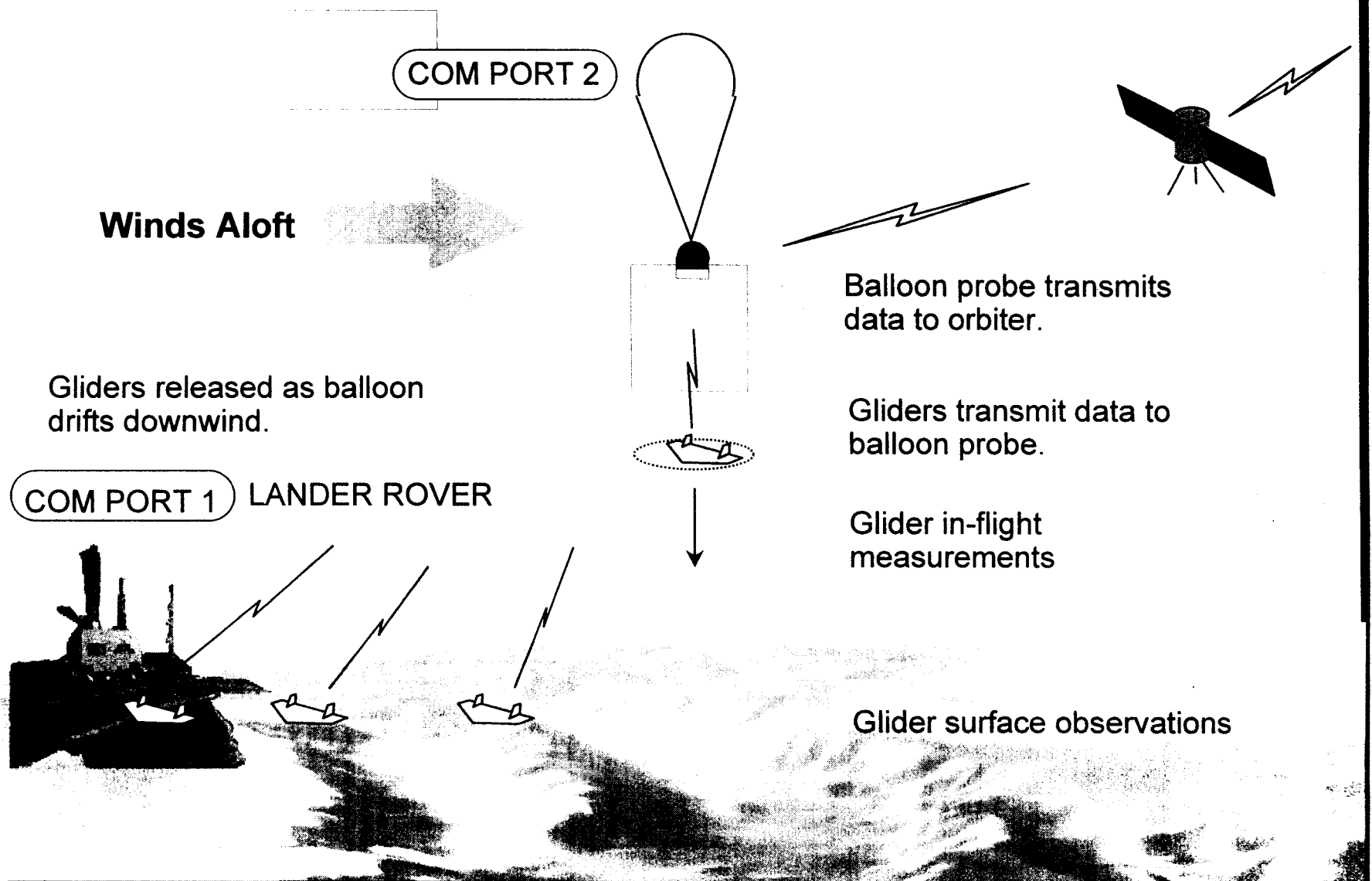
# Biomorphic Glider Deployment Concept: Larger Glider Deploy/Local Relay



## Biomorphic Glider Deployment Concept: Balloon Deploy/Balloon Relay)



# Biomorphic Glider Deployment Concept: Balloon Deploy/Dual Relay



# Biomorphic Gliders

- Small, simple, low-cost system ideal for reconnaissance and wide-area dispersion of sensors and small experiments.
- Payload mass fraction 50% or higher.



		Baseline			
Total Mass (M)	=	57	75	250	500 g
Payload (P)	=	32	45	150	300 g
P/M fraction	=	56	60	60	60 %
Wing Span	=	0.19	0.25	0.50	0.76 m
Wing Area	=	0.014	0.021	0.071	0.143 m <sup>2</sup>
Volume	=	168	300	1700	5200 cm <sup>3</sup>
Flight Speed	=	90	90	90	90 m/s
Range	=	50	55	72	83 km
Duration	=	590	650	800	1300 s
Glide Ratio	=	5.3	5.8	7.5	8.6
Starting Alt.	=	10	10	10	10 km

- Performance calculations based on conditions at 5 km altitude on Mars.
- Volume based on projected area x mean thickness x 1.2



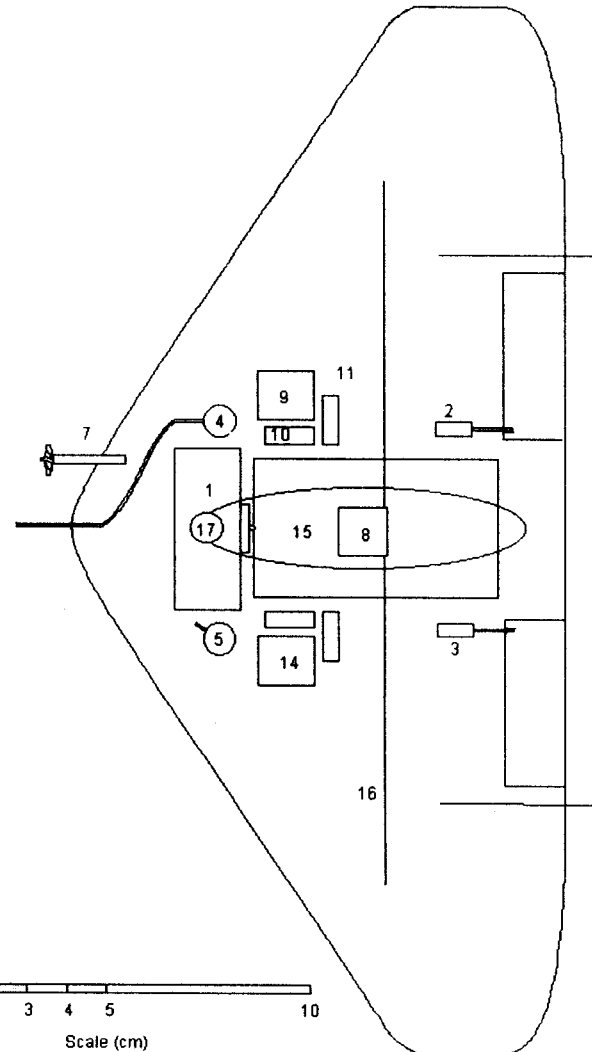
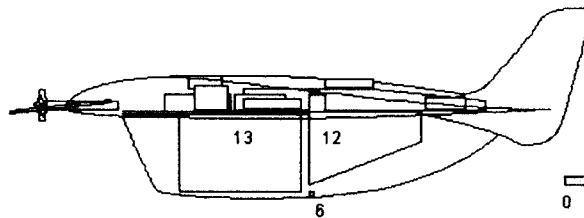
# 75 g Biomorphonic Glider Internal Arrangement

## • System Components

1. Battery, Li 400 mAh\*\*
2. Right elevon servo
3. Left elevon servo
4. Total pressure sensor
5. Static pressure sensor\*\*
6. Temperature sensor\*\*
7. Airspeed sensor\*\*
8. Sun position sensor\*\*
9. Flight controls computer
10. Pitch rate sensor (2)
11. Roll rate sensor (2)
12. Surface experiment\*
13. Camera\*
14. C & DH\*
15. Communications\*
16. Antenna\*
17. IR sensor\*

\* Payload elements

\*\* Shared payload/aircraft



# 75-g Biomorphic Glider Mass/Power Budgets

Item	Mass (g)		Peak Power (W)	Average* Power (W)	Description
	Glider	Payload			
1 Battery	7.0	7.0	-	-	Li 400 mAh, LTC-311
2 Right elevon servo	0.5		0.200	0.200	AV experience, micro geared servos
3 Left elevon servo	0.5		0.200	0.200	
4 Total pressure sensor	1.5		0.010	0.010	
5 Static pressure sensor	1.5		0.010	0.010	IMMI IMP 2000
6 Temperature sensor		0.2	0.025	0.025	Si or Pt chip** [Iksan, Jumo]
7 Airspeed sensor	1.5		0.005	0.005	Servo motor/anemometer
8 Sun position sensor	1.0		0.005	0.005	Four-element photocell
9 Flight controls computer	1.0		0.050	0.050	AV experience, incl. some A-D conv.
10 Pitch rate sensor (2)	2.0		0.120	0.120	AV experience, Murata piezoceramic
11 Roll rate sensor (2)	2.0		0.120	0.120	
12 Surface experiment		10.0	10.000	0.050	Payload reserve***
13 Camera		20.0	0.250	0.050	JPL design, miniature camera
14 C&DH		2.0	0.050	0.050	Incl. some A-D conv. for science instr.
15 Communications		5.0	10.000	2.000	JPL/Caltech/AeroVironment design
16 Antenna		0.3	-	-	JPL/Caltech/AeroVironment design
17 IR sensor		0.3	0.200	0.200	***
18 Airframe/IC/Misc.	12.0		-	-	Composite/ribbon/misc.
Subtotal	30.5	44.8			
<b>Total</b>	<b>75.3</b>		<b>21.245</b>	<b>3.095</b>	

\* Average power consumed with duty cycle over 600 s flight.

\*\* Data reflects device noted or next generation of device.

\*\*\* TBD

Note: Battery mass shared between payload and glider systems.

# Glider Locating Strategy

- **Position Inferred from Data**

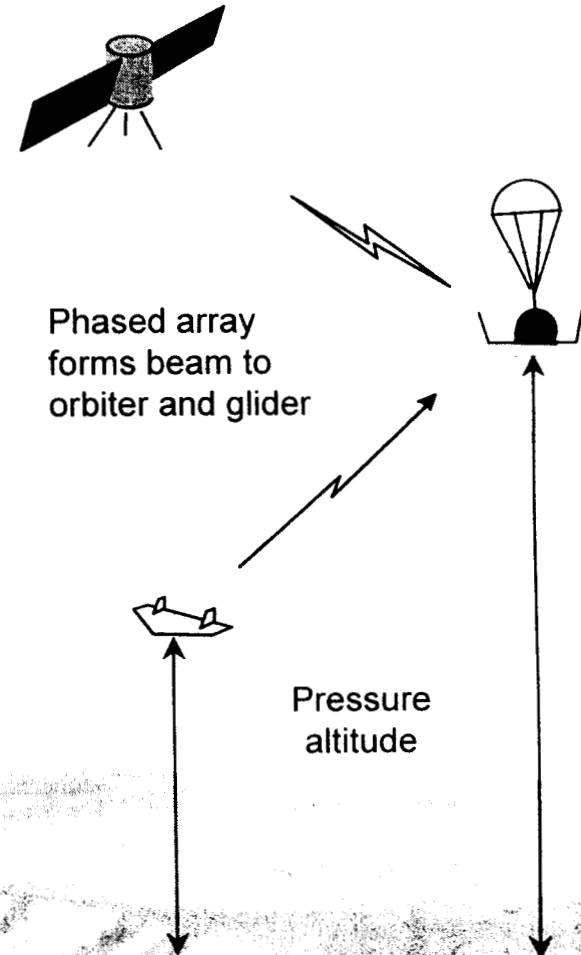
- Entry point + flight plan + glider performance + pressure altitude + images => approximate position

- **Probe Relay Phased Array**

- Glider position relative to probe determined by beam direction and glider pressure altitude
- Probe approximate position tracked by orbiters or using same phased array and orbiters

- **Options**

- Lander equipped with phased array



# System Component Descriptions

## 15. Telecommunications

- The proposed communication plan for the gliders and the lander/relay is based on a self-organized, self-routing network, which changes dynamically during the flight and after landing. The network is based on short-range communication between the glider to route the information to the lander/relay by forming a self-configured, amorphous network of multiple hubs (gliders).
- The glider transceiver will be implemented using monolithic integrated circuit technology to minimize the number of discrete components and hence lower the cost, failure susceptibility, and weight of the glider units, allowing them to carry payload and achieve longer data collection lifetime. The possibility of direct communication between the gliders and the orbiter (at a much lower rate) also makes the system more tolerant to possible failures in the relay unit. A glider transceiver weighing ~ 5 g and consuming less than 2 W total average power in a package of < 3 cm x 6 cm x 1 cm, heat sink included, can be designed and developed. 900 MHz is selected to be the optimum choice of communication frequency both from link performance and monolithic integrated circuit implementation considerations

# Glider Comm Strategy

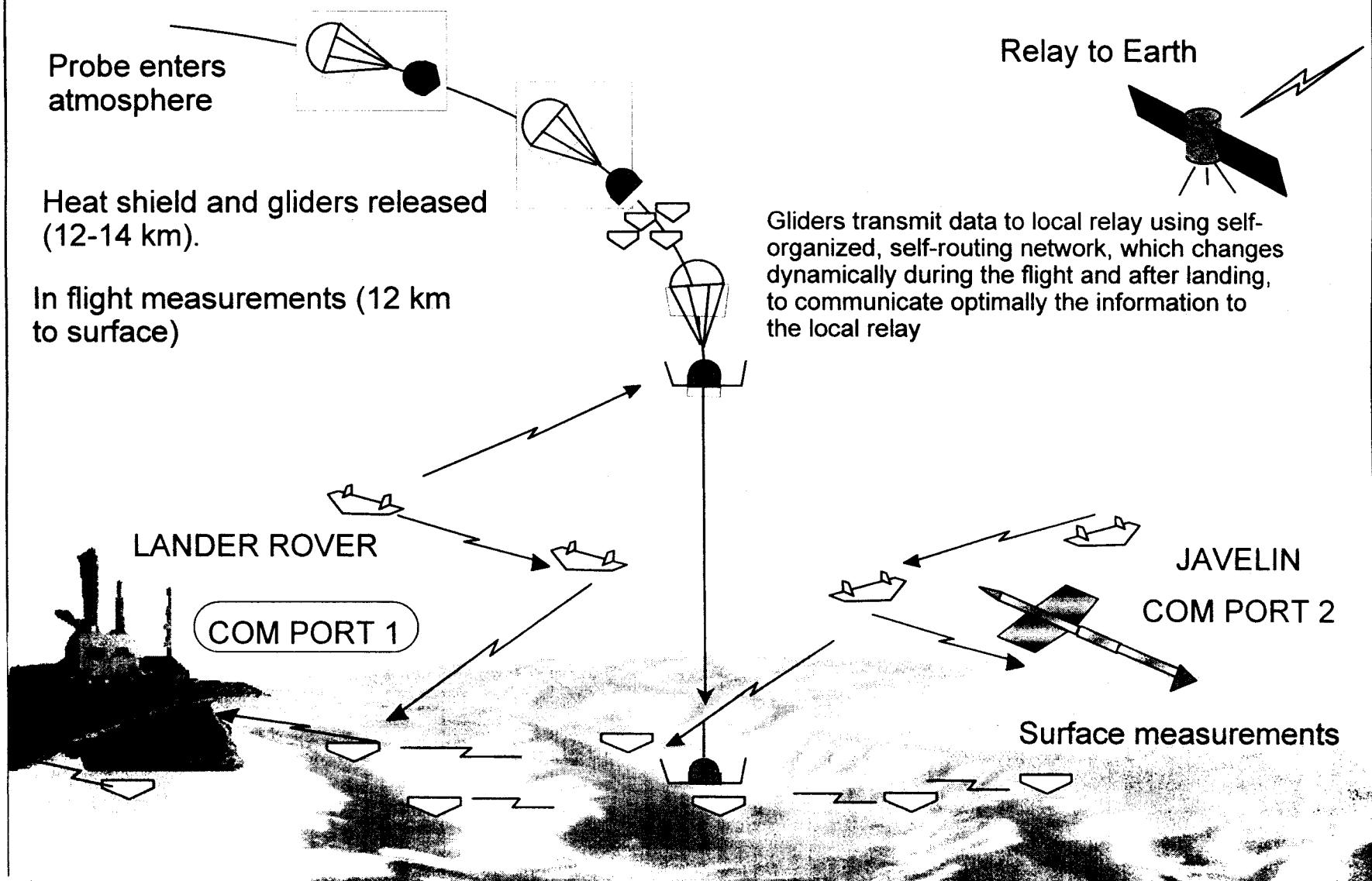
- **Entry Probe as Comm Relay**

- Vantage point above gliders with lower rate of descent, insuring good comm link even with gliders on surface
- Gliders can transmit using optimal self-organized, self-routing network
- Can tailor comm design to mission
- Entry probe becomes lander and maintains comm link to glider network for long-term surface measurements

- **Options**

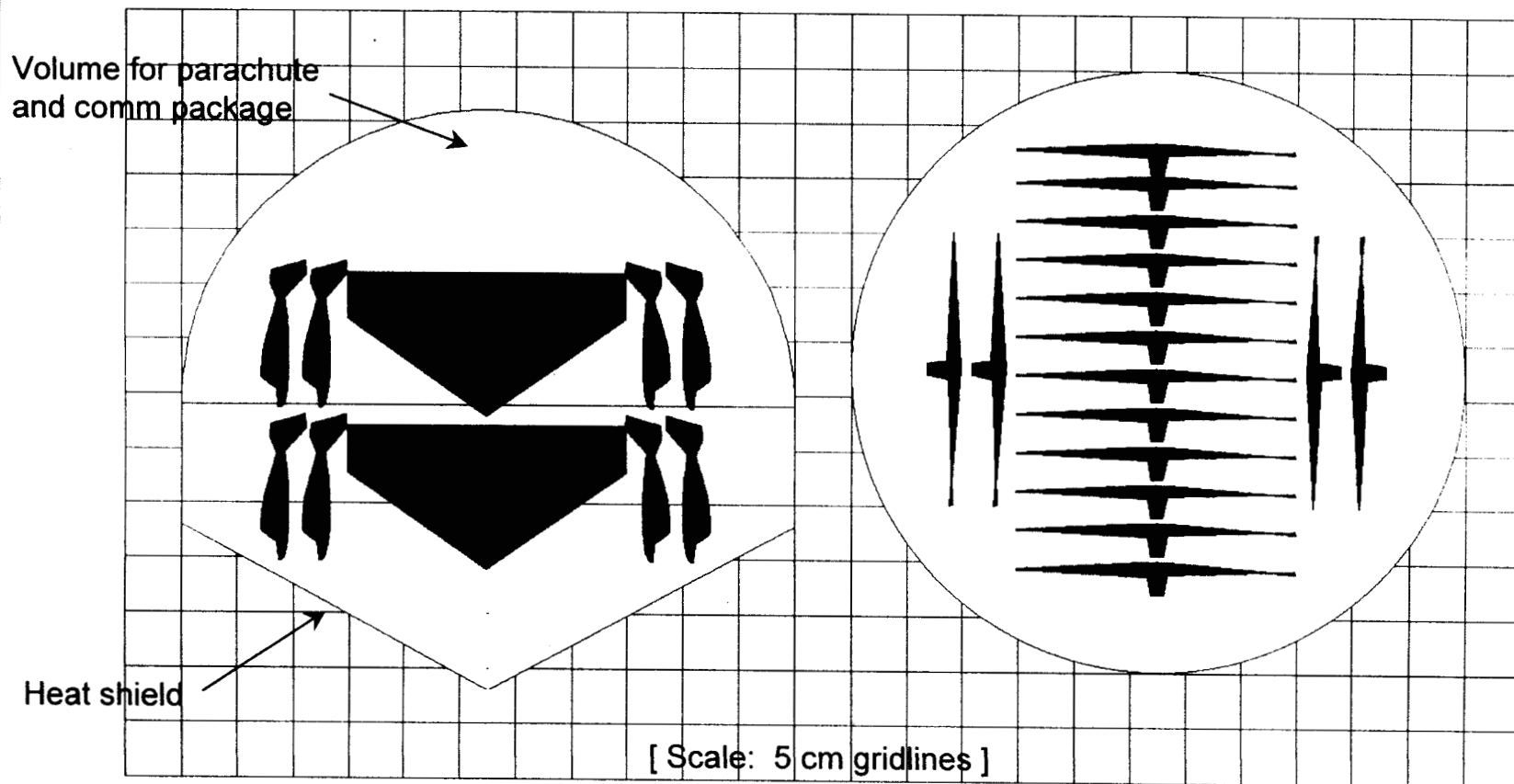
- Use existing lander as comm relay
  - low cost
  - limits site selection
  - risk that entry error puts some gliders out of range
- Deploy separate lander
  - permits site flexibility
  - added cost

# Biomorphic Glider Deployment/Telecommunication Concept



## 75-g Biomorphic Glider/Probe Integration

- 32 gliders packaged into a Arianne Structure for Auxiliary Payload (ASAP) compatible self-righting probe.



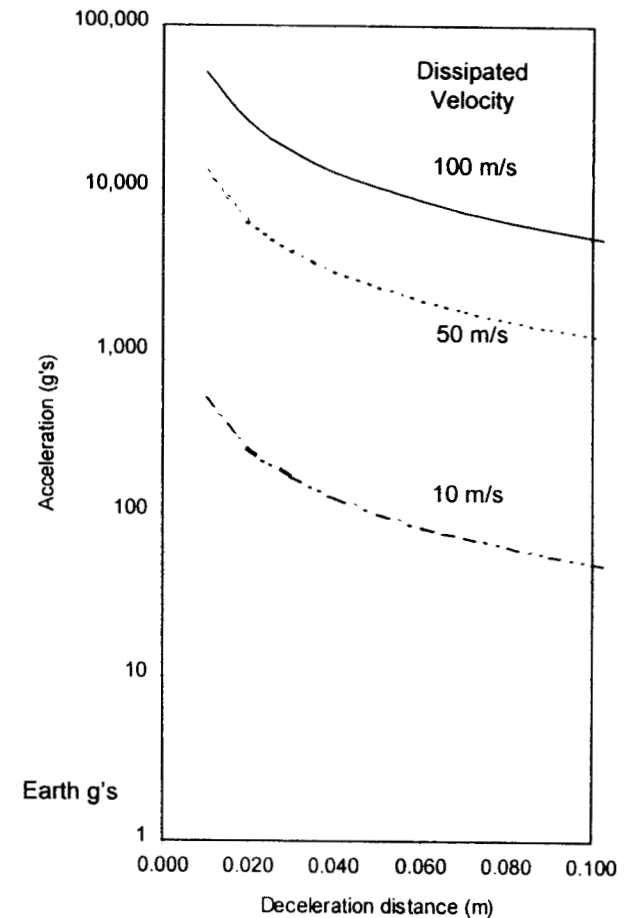
# Biomorphic Glider Landing Survivability

## • Initial Conditions

- 72 m/s horizontal flight speed at 0 km (on surface of Mars)
- 13 m/s descent rate at 0 km

## • General Considerations

- Impact trajectory is at an angle to flat surface. Some gliders may have a direct impact on a rock and not survive,... but there are many gliders.
- Electronics and sensors are all very low-mass integrated or discrete surface-mounted devices designed for several 1000's of g's - need roughly 2 cm to dissipate half the flight speed.
- Battery has highest mass. Can be mounted with crush zone and wire leads for power to the PCBA so that it can break free and not lose electrical connection.
- Surface experiment most vulnerable; MEMS technology most likely to survive hard landings.
- Airframe and flight subsystems are expendable.





# Objective - Atmospheric Science

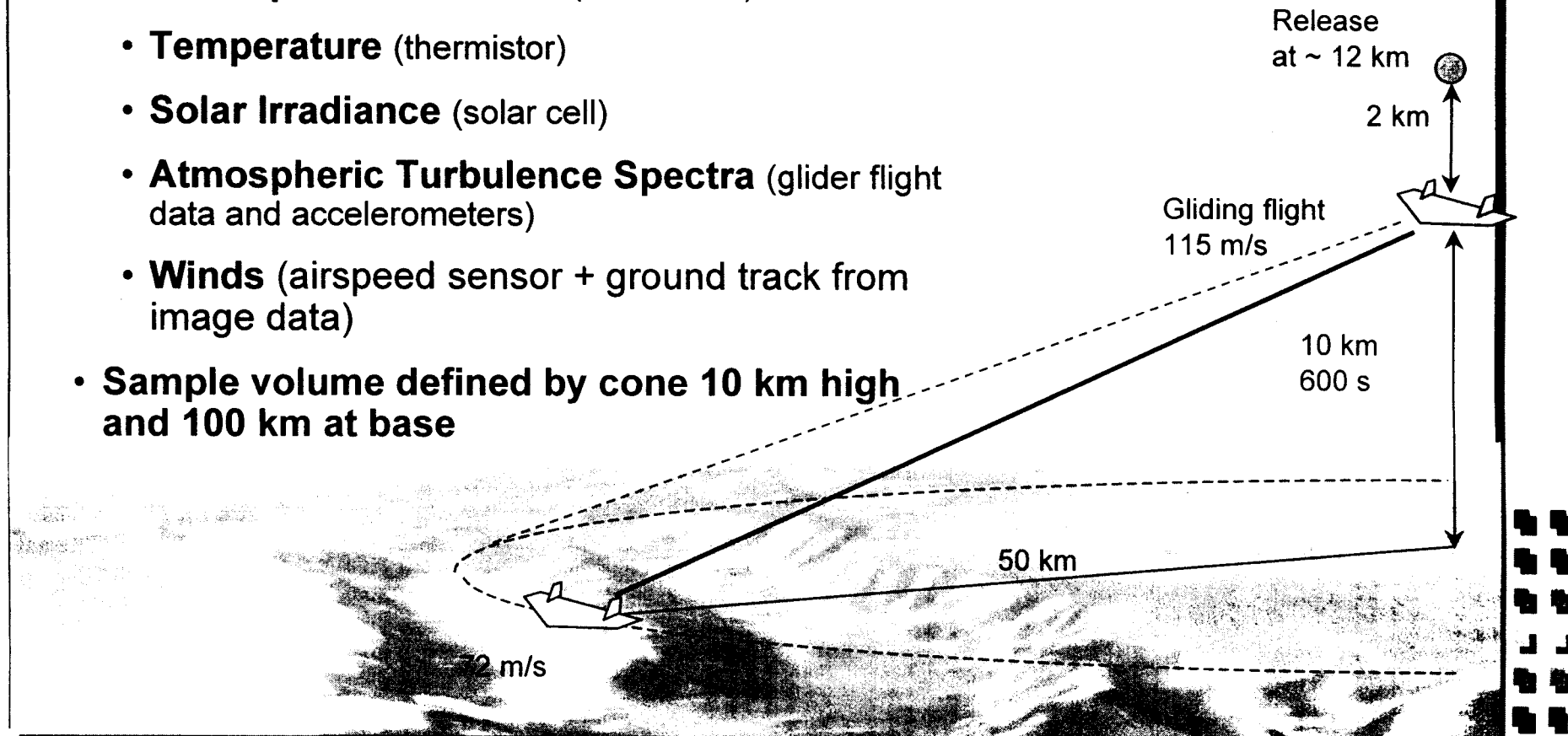
- **VALIDATION AND PREDICTION OF GLOBAL CIRCULATION MODELS BASED ON THE NEAR SURFACE ENVIRONMENTAL DATA AND BOUNDARY LAYER DATA**
- **ADDRESS MESOSCALE METEOROLOGY (T, P, Wind, Opacity). TARGET GLIDER CLUSTER TO AN AREA (~ 100 km x 100 km) THAT IS DIVERSE**
- **SPECIFIC TARGET SITES:**
  - **mouth of a canyon**
  - **edge of a polar cap**
  - **outflow channels**
- **TIME THE RELEASE OF BIOMORPHIC GLIDERS TO OBTAIN THE MEASUREMENT OF EPHEMERAL PHENOMENA SUCH AS DUST STORMS**

# Biomorphic Glider In-Flight Measurements

## • Meteorology

- Multiple gliders permits analysis of temporal and spatial variations in measurement
  - Atmospheric Pressure (transducer)
  - Temperature (thermistor)
  - Solar Irradiance (solar cell)
  - Atmospheric Turbulence Spectra (glider flight data and accelerometers)
  - Winds (airspeed sensor + ground track from image data)
- Sample volume defined by cone 10 km high and 100 km at base

Total number of measurements =  
 # gliders  
 X # measurements/s  
 X flight time



## WHY ATMOSPHERIC SCIENCE USING GLIDERS?

The lower atmosphere is difficult to measure from orbit; infrared remote sensing techniques typically cannot separate the atmospheric contribution from that of the surface in the lowest scale height. Yet the boundary layer, where the surface interaction takes place, is of great importance, being the location of energy transfer in the form of friction, radiation, and conduction.

Direct instrumentation of the lower atmosphere is difficult; usually towers and balloons are employed for this purpose on Earth. The former are massive and the latter temporary. Where horizontal change occurs in the surface, such as in canyons, a network of balloons would be required to observe the range of phenomena. Such topographic regions are important because the winds arising there may help in the origination of dust storms. Dust storms of Martian intensity are unique, and their formation is one of the main problems of planetary atmosphere dynamics.

Glider networks, although temporary, provide a way to sample both laterally and vertically within a short time period, from a single originating point. The spatial scale of coverage, as wide as 100 km, is adequate to span large Martian canyon boundaries. The sampling rate can be high enough to resolve the relevant small-scale phenomena within the lowest 10 km. Gliders can be directed to cover particular directions, unlike balloons.

An additional benefit of gliders is the ability to image during descent, providing proof of glide path, determination of wind (together with airspeed), and geologic context at a large range of spatial resolutions.

# Objective: Imaging & Surface Science

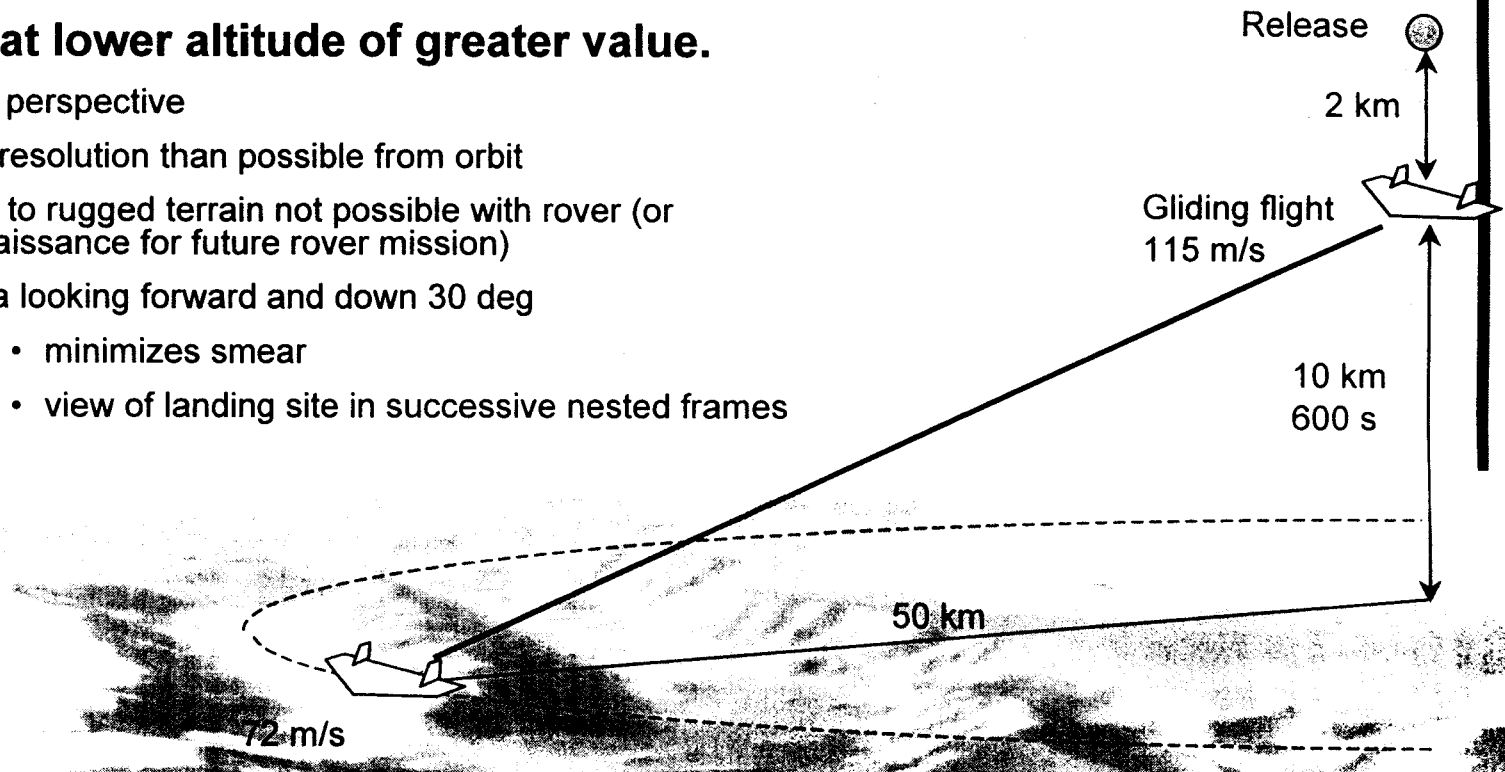
- Detailed close-up imaging and mapping of the terrain to enable site selection of potential exobiological sample areas
- Imaging of Valles Marineris
  - one single site rich in geologic units
  - study stratigraphic column top to bottom along the canyon wall
  - optimum science sample site
- Deployment of surface science payloads on potentially interesting but hard-to-access locations

# Biomorphic Glider In-Flight Measurements

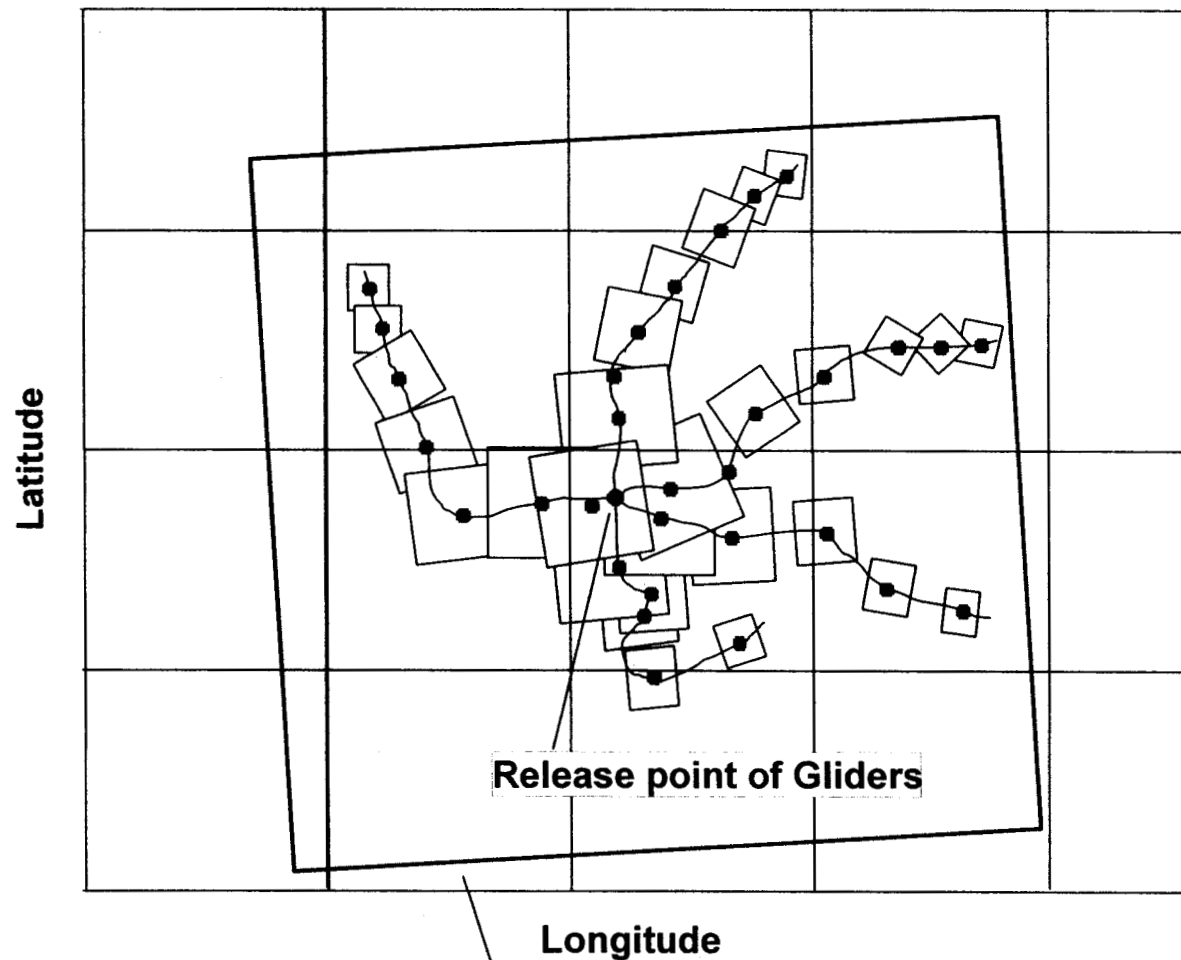
## • Imaging

- Images at high altitude of limited science value compared to orbiter (resolution, FOV).
  - Provides context for low-altitude images
- Images at lower altitude of greater value.
  - Unique perspective
  - Higher resolution than possible from orbit
  - Access to rugged terrain not possible with rover (or reconnaissance for future rover mission)
  - Camera looking forward and down 30 deg
    - minimizes smear
    - view of landing site in successive nested frames

Total number of measurements =  
 # Gliders  
 X # images



## Footprints of Descent Images



Context frame acquired by carrier vehicle, 100 km x 100 km area

# Miniature Digital Camera Assembly

- **Key Elements**
    - **Active Pixel Sensor (APS) Imaging Chip**
      - 2-D imaging array using CMOS technology
      - On-chip digital circuitry gives full programmable control to enable digital camera-on-a-chip operation.
      - On-chip camera control functions include frame rate, exposure parameter, electronic shuttering, analog-to-digital readout.
      - Mass: 5 g
      - Grayscale: 8 - 10 bit
      - Aperture size: 5 mm x 5 mm (512 x 512 pixels, 7.9  $\mu$ m pixel pitch)
      - Power consumption: 50 mW - 250 mW ( varies with frame size)
    - **Imaging Lens**
      - 1 cm diameter, 50 mm focal length, lightweight plastic lens
      - Mass: 3 g
  - **Customized packaging**
    - A customized miniature digital camera would be achieved by integrating an imaging lens on top of a camera-on-a-chip circuit board with the following specifications
      - Mass: 20 g
      - Power consumption: < 250 mW
      - Speed: 30 - 100 frames/s
- The above includes mass margin for an innovative stereo camera package to be designed using a dual lens image input fused onto a single APS imaging chip

# Biomorphic Glider Surface Measurements

## • Large Number of Samples, Coverage and Diversity

- Total number of sites = number of gliders
- Total area ~ 100 km circle, permits broad area coverage of interesting geological regions

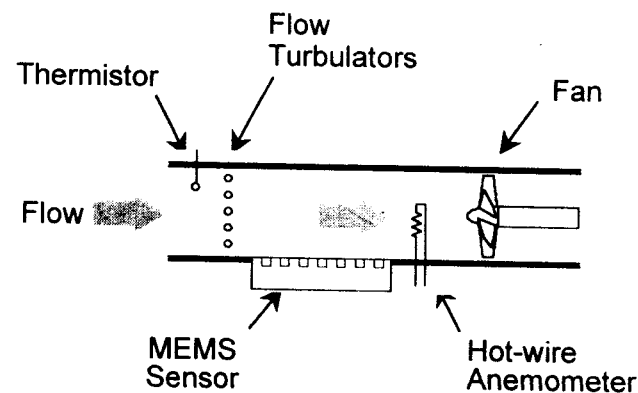


## • Distributed In-Situ Experiments

- Chemical Composition

### Gas Source

- Evolved gasses, (heat activated)
- Chemical reaction
- Drill probe, H<sub>2</sub>O/CO<sub>2</sub> ice concentration vs. soil depth





# Biomorphic Glider Surface Measurements

## • Long-Term Distributed Surface Observations

(diurnal variation of relevant parameters)

- Seismic Measurement (accelerometers)
- Atmospheric Pressure (pressure transducer)
- Temperature (thermistor)
- Solar Irradiance (solar cell)
- Near-IR sensor to help differentiate water ice clouds from dust clouds

(Would require additional solar cells for power)

## • Imaging

- Potential for interesting data if camera survives landing:
  - images showing local variation in soil/rock/terrain roughness on a scale relevant to rover mobility for future missions
  - local landscape images taken from perspective not obtainable from orbit from areas not accessible by rover



## **SCIENCE APPLICATIONS**

**....WHICH WOULD BE ENABLED/ENHANCED BY SUCH EXPLORERS.....**

- **VALLES MARINERIS EXPLORATION**

- **ONE SINGLE SITE RICH IN GEOLOGIC UNITS**
- **STUDY STRATIGRAPHIC COLUMN TOP TO BOTTOM  
ALONG THE CANYON WALL**
- **OPTIMUM SCIENCE SAMPLE SITE**

**....imager, temperature sensor, pressure sensor, sniffer: e-nose, individual gases, elements, etc.**

- **SCOUTING FOR CONDITIONS COMPATIBLE WITH LIFE TO LEAD US TO THE SPOTS  
THAT MAY HOLD SAMPLES OF EXTINCT/EXTANT LIFE**

- **WIDE-AREA SEARCH WITH INEXPENSIVE EXPLORERS EXECUTING DEDICATED  
SENSING FUNCTIONS**

**....Individual gases, sniffer: e-nose, chemical reactions, pyrotechnic test, elements,  
specific amino acids, signatures of prebiotic chemistry, etc.**

- **GEOLOGICAL DATA GATHERING:**

- **DISTRIBUTED TEMPERATURE SENSING**
- **SEISMIC ACTIVITY MONITORING**
- **VOLCANIC SITE**

**....Multitude of explorers working in a cascade or daisy-chain fashion  
cooperatively to fulfill task**

# Biomorphic Issues for Future Incorporation

- **Glider Navigation**

- Simple => Flight plan/navigation based on Sun angle (similar to bees) or GPS position
- Intelligent => Use camera data to steer to interesting targets, neural site selector logic unit
- Cooperative => Communication between gliders to maximize target diversity.

- **Glider Performance**

- Soaring techniques => Glider performance (range and duration) can be greatly extended by taking advantage of atmospheric air currents much in the same way soaring birds use orthographic and convective currents to sustain flight for long periods of time and to cover great distances without flapping. (Probably not very useful on Mars, but may be of great value on Jupiter or Venus)

- **Flight Controls**

- Possibility of capturing sensory-flight control mapping transformation onto neural chips will be explored to obtain goals of damage tolerance/adaptive controls

# Biomorphic Glider Deployment/Telecommunication Concept (long term)

Probe enters atmosphere

Heat shield and gliders released (12-14 km).

In-flight measurements (12 km to surface)

Gliders fly preset flight plans based on GPS waypoint navigation.

Marsnet GPS, Relay to Earth

Gliders transmit data to orbiter using self-adaptive, self-routing techniques.

Surface measurements

# Glider Navigation Strategy (long term)

- **GPS Navigation**

- Requires miniature GPS technology for gliders and Marsnet implementation
- Each glider has unique flight plan using GPS waypoint navigation referenced to actual release point
- Functional day or night

- **Adaptive Targeting to Maximize Science Return**

- Gliders provided list of prioritized science target signatures
- Glider flight trajectory can be adjusted to take advantage of high-priority science targets captured in camera/sensor FOV
- During comm process, each glider notes which class of target neighbors are focused on and determines need to adjust flight plan to maximize target diversity (eliminates problem of all gliders going after same high-priority target)

# Glider Comm Strategy (long term)

- **Local Relay Utilizing Self-Adaptive Phased Array (potential innovative concept)**
  - **Motivation**
    - Mass and volume constraints limit RF capability of individual glider to communicate directly with orbiter in current telecom plan
    - Total mission mass, cost, and volume can be minimized (or number of gliders maximized) by having relay that can locate gliders
    - Comm strategy becomes very fault tolerant (i.e., not dependent on any single system to operate, can tolerate failure of several gliders without impacting overall performance)
  - **Approach**
    - Use self-adaptive phased array antenna techniques on local relay
    - Orbiter system used as reference, can use two “chirps” in succession to determine modulation phasing for each individual glider
    - Gliders communicate between themselves and share data to be transmitted before transmitting to local relay

# Glider Locating Strategy (long term)

- **Position Determined Using GPS**

- Requires miniature GPS technology for gliders and Marsnet implementation
- Functional day or night

- **Position Inferred from Data**

- Entry point + flight plan + glider performance + pressure altitude + images => GPS position validation

## **CONCLUSIONS**

- **BIOMORPHIC EXPLORERS IS A VIABLE TECHNOLOGY THAT WILL ENABLE NEW COOPERATIVE EXPLORATION MISSIONS**
- **“BIOMORPHIC SCIENCE GLIDER” FOR MARS WITH FOLLOWING FEATURES:**
  - **MASS < 100 g**
  - **PAYLOAD FRACTION > 50%**
  - **LONG RANGE ~ 50-100 km**
  - **SOLAR NAVIGATION****IS AERODYNAMICALLY POSSIBLE**
- **BIOMORPHIC GLIDER MISSIONS CAN BE IMPLEMENTED IN SEVERAL DIFFERENT SCENARIOS, AND, THEREFORE, BIOMORPHIC EXPLORERS CAN BE SENT RAPIDLY IN THE MASS RESERVES OF UPCOMING ORBITER, LANDER, OR BALLOON MISSIONS**
- **BIOMORPHIC EXPLORERS IS A TECHNOLOGY PUSH ON**
  - **MINIATURIZATION & INTEGRATION OF PAYLOAD**
  - **COOPERATIVE COMMUNICATION INNOVATIONS**
    - **monolithic transceiver integration**
    - **dynamic networks of self-routing optimal comm-interlinks**
  - **BIOMORPHIC FLIGHT SYSTEMS**
  - **BIOMECHATRONIC SURFACE SYSTEM INNOVATIONS**



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